Superconductive Devices

ALBERT E. SLADE  HOWARD McMAHON
NONMEMBER AIEE  NONMEMBER AIEE

Over the past 2 years there have been several suggestions advanced for computer devices which utilize the unique properties of superconductors. Some of these take advantage of the strong nonlinear dependence of resistance on magnetic field which makes possible the construction of high-speed switches. Other proposed devices utilize the ability of a superconductor to carry a so-called persistent current which offers the possibility of constructing memory elements.

To date, a variety of devices of both types have been constructed and studied, and while many developmental problems remain to be solved, there is a strong conviction among those who are working in the field that the phenomenon of superconductivity will eventually provide useful computer devices.

Superconductivity

Superconductivity was discovered by Kammerlingh Onnes in 1911. While in the process of extending electrical resistance measurements to the newly available liquid helium temperature range he discovered that the resistance of mercury dropped abruptly to zero at approximately 4 degrees above absolute zero. Soon thereafter many other metals were observed to exhibit similar characteristics. Onnes recognized that he had discovered a completely new state of matter and he named it the superconductive state.

Since absolutes are rare in nature it became a matter of considerable interest to determine if the resistance in the superconductive state is truly zero or only exceedingly small. Many experiments have been performed to detect any small residual resistance and it is now generally accepted that the resistance is indeed zero. It has been observed that a current induced in a closed superconductive circuit will continue to flow for years with no measurable attenuation. Currents of this type are known as persistent currents.

It was soon found that a superconductive circuit cannot carry an indefinitely large current. In each case there is a critical current above which the metal recovers its normal resistance. Further investigation revealed that the superconductive transition is determined not only by the temperature but also by the magnetic field strength at the surface. The relationship of magnetic field and temperature for several known superconductors is shown in Fig. 1. Only the total strength, but not the direction, of the magnetic field at the superconductive boundary is effective in restoring the normal state. The limit on current-carrying ability of a conductor has been shown to be consistent with the local magnetic field strength resulting from the current.

A superconductor is unusual not only because of its infinite conductivity, but also because of its remarkable magnetic properties. It is to be expected that the magnetic induction inside an infinitely good conductor will remain constant with time, because any change in external magnetic field will result in the generation of undamped eddy currents which will cancel the effects of the external field change. It is also to be expected that any current flow will be confined to the surface of the body. Both of these conclusions can be derived readily from Maxwell's induction equation.

At first it was thought that this argument, which established B as a constant, was adequate to characterize completely the superconductive state. However, in 1933, it was discovered that the magnetic induction is not only invariant but equal to zero at all times, a fact which cannot be derived from the criterion of zero resistance. Thus the ideal superconductive state is not only infinitely conducting but, in addition, is also perfectly diamagnetic.

The Intermediate State

It has been found that a real superconductor cannot be described simply as a body of zero electrical resistance. In fact, the only superficial resemblance between real and ideal superconductors is that the electrical resistance is exactly zero for sufficiently small current flow. The precise way in which real superconductors differ from ideal ones is exceedingly complex and depends on such things as physical and chemical structure, amount of mechanical strain, shape of conductor, thickness of metal, and other factors.

Real superconductors, particularly in the form of thin films, show large deviations from ideal behavior. For example, the ability to carry current without becoming resistive is often lower than the ideal value by an order of magnitude. Also the strength of an externally imposed magnetic field required to destroy the superconductive state may be much larger than ideal.

Currently proposed theories of the intermediate state picture it as being composed of thread-like filaments of superconductive state and normal state somewhat like the fibers of a rope. A surface energy, either positive or negative, is ascribed to the boundary surface separating the superconductive from normal regions. This model is moderately successful in explaining most of the observed complexities, but is not sufficiently complete at present to eliminate the need for experimentation in the design of superconductive devices.

The Cryotron

Dudley Buck was the first to consider seriously the potentialities of superconductivity in relation to computers. He proposed to utilize the sharp resistive

Fig. 1. Critical field versus temperature for various superconductors

Fig. 2. Comparison of a transistor, a germanium diode, a cryotron, and two magnetic cores

Slade, McMahon—Superconductive Switching

From the collection of the Computer History Museum (www.computerhistory.org)
sufficiently large to be used to energize a cryotron circuitry it is only necessary for the gain to be greater than one, since the resistive control coil necessary to make the gate Ic(min)

is the maximum current the gate can carry resistive state. The niobium control coil flux cannot penetrate the core and therefore, the effective diameter of the coil is reduced. The core must, of course, remain superconducting when the gate is quenched and it must be electrically insulated from the gate.

Frequency Response

The frequency response of a cryotron circuit is governed by the L/R-time constant of the current path which is in the process of being changed. In each circuit considered there will be a number of inductances and a number of resistances. However, the fundamental time constant of the cryotron as a device can be considered to be the inductance of a single control coil divided by the resistance of a single gate.

Table 1. Characteristics of Various Active Superconductive Switches

<table>
<thead>
<tr>
<th></th>
<th>Present Wire-Wound Cryotron</th>
<th>Proposed Wire-Wound Cryotron with Gate Deposited on Superconducting Core</th>
<th>Present Vacuum Deposited Cryotron</th>
<th>Research May Make This Possible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity at 4.2 degrees K</td>
<td>10^-6 ohm-centi-</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Cross-sectional area of gate</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Length of gate that is quenched</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Resistance of quenched area</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Inductance of control</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Inductance of gate</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>L/R time constant</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Gain</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Gain X R/L</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

*Note: Very little is known about the thermal time constant of a cryotron. It is very likely that heat dissipation will limit the maximum repetition rate.*

The current gain of a cryotron can be defined as Ig(max)/Ic(min), where Ig(max) is the maximum current the gate can carry without restoring its own resistance, and Ic(min) is the minimum current in the control coil necessary to make the gate resistive. If this gain is greater than one, then the current flowing in a gate can be sufficiently large to be used to energize a control coil connected in series. In cryotron circuitry it is only necessary for the gain to be greater than one, since the current flows in series through all of the output gates and coils. If it were necessary for the output of a single flip-flop to drive several loads that are in parallel, then the gain would have to be much greater.

However, in cryotron circuits, because of the zero d-c impedance, it is not feasible, in general, to utilize parallel circuits and a current gain slightly in excess of unity is therefore adequate. The ability to connect an indefinitely large number of controls in series with a single gate even though the current gain is only slightly greater than unity is advantageous under certain circumstances. However, the advantage is purchased at the expense of reduced frequency response, because of the increased inductance.

Current Gain

The current gain of a cryotron can be defined as Ig(max)/Ic(min), where Ig(max) is the maximum current the gate can carry without restoring its own resistance, and Ic(min) is the minimum current in the control coil necessary to make the gate resistive. If this gain is greater than one, then the current flowing in a gate can be sufficiently large to be used to energize a control coil connected in series. In cryotron circuitry it is only necessary for the gain to be greater than one, since the current flows in series through all of the output gates and coils. If it were necessary for the output of a single flip-flop to drive several loads that are in parallel, then the gain would have to be much greater.

However, in cryotron circuits, because of the zero d-c impedance, it is not feasible, in general, to utilize parallel circuits and a current gain slightly in excess of unity is therefore adequate. The ability to connect an indefinitely large number of controls in series with a single gate even though the current gain is only slightly greater than unity is advantageous under certain circumstances. However, the advantage is purchased at the expense of reduced frequency response, because of the increased inductance.

Frequency Response

The frequency response of a cryotron circuit is governed by the L/R-time constant of the current path which is in the process of being changed. In each circuit considered there will be a number of inductances and a number of resistances. However, the fundamental time constant of the cryotron as a device can be considered to be the inductance of a single control coil divided by the resistance of a single gate.

The time constant of the early wire-wound cryotron is about 100 microseconds. This obviously leaves much to be desired and is undoubtedly the most severe disadvantage of the cryotron as originally conceived.

Since the time constant is L/R or some small multiple, it can be shortened by reducing L or increasing R. Increasing R by increasing the length of the cryotron is not fruitful because L increases at the same rate as R. R can be increased by reducing the diameter of the wire but this raises many practical problems related to construction feasibility. R could also be increased by depositing a thin film of gate material on a nonconducting rod, thereby increasing the resistance of the gate because of its reduced cross-sectional area but keeping the size of the device unchanged. The resistance might also be increased by using an alloy of higher resistivity than tantalum.

There are fewer possibilities of reducing the inductance of the control coil. Reducing the diameter of the coil would reduce its inductance, but in order to preserve current gain it would be necessary to increase the number of turns per inch in proportion, which would cancel the advantage. The inductance may be reduced considerably by using a film gate as previously mentioned where the inside of the rod is filled with a superconductor. The control coil flux cannot penetrate the superconducting core and therefore, the effective diameter of the coil is reduced. The core must, of course, remain superconductive when the gate is quenched and it must be electrically insulated from the gate.

In Table 1, the gain and time constant of the present cryotron and several proposed cryotrons are tabulated for comparison. Thus, it appears almost certain that an increase of two orders of magnitude can be achieved in the speed of cryotrons when used as active circuit components.

Cryotron Circuitry

Buck has discussed a variety of logical circuits that utilize cryotrons. The nature of cryotron circuits differs considerably from those which use vacuum

From the collection of the Computer History Museum (www.computerhistory.org)
tubes and transistors. Cryotrons more nearly resemble relays and as might be expected the logical circuitry is also similar. Because of the exceptionally low resistance involved, a current source is used. The current is usually allowed the choice of two paths, one of which is resistive, the other superconductive. Because of the infinite resistance ratio between the resistive gate and the superconductive gate, all of the current flows in the superconductive path.

A flip-flop with input and output gates, such as is shown in Fig. 3, illustrates the use of cryotrons in switching circuits. The actuating current \( I_{FF} \) is a constant regardless of the state of the flip-flop. If the current is flowing through the gate of cryotron \( A \) then it also flows through the control of cryotron \( B \), making gate \( B \) resistive. The circuit is therefore bistable, because the current, once established in one of the two possible paths, will lock in by causing the other path to be resistive.

The state of the flip-flop can be determined by measuring the resistance of the output gates; one gate will have zero resistance, the other a finite resistance. The state can be changed by energizing the control coil of the appropriate input cryotron, thus imposing a resistance in the conductive path and causing the current to divert into the alternative circuit. The characteristics and operation of the flip-flop and other cryotron circuits have already been described in more detail in other papers.\(^1\)\(^2\)

### Multiple Gate Devices and Circuits

An important distinction between transistor and cryotron circuits is the possibility in the latter of combining many devices into one. In some cryotron circuits the over-all system is in reality a single device.\(^3\) Fig. 4 illustrates a 4-position switch in which the current labelled \( I_{source} \) has a choice of four paths, each of which threads a unique course through the control coils. When the control coils are energized in pairs \( i.e.; X_1 \text{ or } X_2 \) and \( Y_1 \text{ or } Y_3 \), there is one, and only one, superconductive path through the switch. Any number of paths can be added to the switch by increasing the number of pairs of control coils. With ten control coil pairs there can be \( 2^{10} \) or \( 1,024 \) unique paths. It has been pointed out that such a switch could be constructed using more or less conventional weaving techniques. A 1,024-position woven switch using 0.002-inch wires would resemble a rope about a quarter of an inch in diameter and about 2 inches in length.

Another circuit similar to the multiple gate switch of Fig. 4 is the woven memory.\(^4\) The woven memory, Fig. 5, is a logical network of multiple-gate cryotrons in which all of the stored information is permanent. Control coils are arranged in pairs, and wires are threaded through either the "one" or the "zero" coil of each pair. The memory differs from the switch in the respect that only a fraction of the possible paths contain a wire. Each wire woven into the memory represents a stored word. All word wires originate at a common junction and terminate at another common junction, and a constant total current is caused to flow through them. For any combination of parallel binary input currents to the pairs of control coils, there is only one possible superconductive path through the memory. If a word wire exists in that path, there will be no voltage drop across the memory. If that word wire were purposely omitted from the memory, the current is forced to flow through the remaining resistive paths. The presence or absence of a word is detected by monitoring the voltage drop across the memory. This type of static memory may be useful in translation and for function tables.

### Vacuum-Deposited Cryotrons

The low switching speed and tedious interconnection problems associated with wire-wound cryotrons has led to a study of vacuum deposition techniques for constructing superconductive switching devices.

A circuit consisting of one or many cryotrons can be made by vacuum-evaporating in succession, layers of suitable metals and insulations through a series of masks. Fig. 6 is a vacuum-deposited, 4-position switch constructed in this manner. It consists of a deposition of tin gates which form the conducting paths of the switch, a subsequent deposition of silicon monoxide insulation in selected areas, a deposition of lead control crossings, and finally a deposition of silicon monoxide encapsulation. Vacuum deposition techniques offer the double advantage of increased switching speed, because of miniaturization, and simplicity of construction. Entire circuits can be made in a single operation, thus eliminating interconnection problems.

Vacuum-deposited cryotrons are still in the research stage. The nature of a thin superconductive film is not well understood at the present time. The restoration of resistance under the influence of external magnetic fields and internal currents cannot be predicted for films of various thicknesses even for pure materials. For this reason it is not possible to predict current gain and frequency response (or switching speed) from existing theory. The third column of Table I indicates the present state of the art for active circuit elements now possible. A considerable improvement is expected with further research and development.

Deposition film techniques of exactly the same kind have been used to construct high-speed passive switches. Fig. 6 is an example of a passive tree switch. Since there is no requirement for current gain in this case, the switching speed is proportional to the inductance of the gate only, and is independent of the inductance of the control. Optimum switching speed would be realized when the length of the
gate conductors is made small compared with the length of gate that can be made resistive. Maximum switching speed has not yet been determined for this configuration.

**Persistent Current Devices**

Several methods for utilizing persistent currents for memory devices have recently been discussed at the Fifth International Low Temperature Conference at Madison, Wisconsin and elsewhere. These devices are based on the establishment of a persistent current in a superconducting loop which will remain indefinitely until its direction is reversed by an external agency. The direction of the current is used to signify the storage of a "one" or "zero" bit of information. The magnitude and direction of the current are determined in a somewhat complicated way by the magnetic or electrical history of the loop. Consider the case of a superconducting ring cooled in a region of zero magnetic field. If it is exposed to an axial magnetic field \( H \), a circulating current will appear in the ring. The current is of such a magnitude and direction that it preserves the initial state of zero flux density within the area encircled by the ring. For a ring of radius \( r \) and a wire assumed to be small in diameter, compared with \( r \)

\[
\frac{dH}{dt} = \frac{L}{R} \frac{di}{dt} + iR = L \frac{di}{dt}
\]

since the resistance \( R \) is zero. Integration gives the current \( i \),

\[
i = \frac{\pi r^2}{L} H
\]

When the imposed field reaches a certain value, the vectorial sum of the field caused by the supercurrent and the imposed field becomes equal to the critical field at the outer edge of the ring and begins to restore resistance to the ring. At this point the total field at the outer edge of the ring is the sum of two terms. The contribution of the imposed field is \( 2H \) because of the distortion of the magnetic field about the circular cross-section of the superconducting wire that forms the ring and the contribution of the circulating current is \( 4i/d \), where \( d \) is the diameter of the superconducting wire. Hence the maximum value of \( i \) is given by:

\[
2H + \frac{4i}{d} = H_{\text{critical}}
\]

As the imposed field is increased further, the circulating current diminishes in such a way that the vectorial sum of the two fields remains at the value \( H_{\text{critical}} \).

Fig. 7 shows a hysteresis plot of the current in a closed ring as a function of the applied magnetic field. The boundaries of the diagram are determined by the requirement that the tangential component of the total magnetic field at any point on the surface of the ring must not exceed the critical field. The diagram can be circumscribed only in the clockwise direction. Any change in \( H \) that does not intersect the boundary produces a reversible change in \( i \) that is completely cancelled when the change in \( H \) is reversed. However, if \( H \) is changed in such a way that it exceeds the diagram boundary, the persistent current remaining in the ring when \( H \) is returned to its original value is permanently altered and may even have a reversed direction.

A superconducting ring is used as a memory element in the following manner. A positive transfer field somewhat less than \( 1/2H_c \) is applied and then removed. A persistent current is thus stored in the ring as represented by point \( B \) in Fig. 7. If the same positive transfer field is again applied and removed, the current will reverse along line \( AB \) and always leave the same persistent current stored in the ring.

A negative transfer field will change the current along line \( BCD \) and the direction of the current is reversed. A positive current can represent a "one"; a negative current, a "zero."

Readout can be accomplished by observation of the net change of flux within the ring. If the persistent current does not change direction, the output is symmetrical and can be integrated to zero; if the persistent current does change direction, the output is not symmetrical, and integration does not yield zero.

Details of various readin and readout schemes have been discussed in recent conferences and publications. Switching times as short as 10 millisecond can be utilized for a memory device similar in principle to the one just described.

Persistent currents can be excited in superconducting loops by other than inductive methods, and several memories have been suggested which utilize such methods. Consider a circuit consisting of two superconducting self-inductances in parallel. Assume one of these to be a straight conductor which, of course, has a very low inductance; and the other to be a coil which has a much larger inductance. When a current pulse is applied to the parallel combination, it will divide according to the ratio of inductances. The straight conductor will carry the most current, and for some critical value, will become resistive due to the strength of its self-field. At this time the current will redistribute itself into the larger inductance. When the current pulse is removed, the straight conductor again becomes superconductive and the energy stored in the larger inductance will cause a current to persist in the ring formed by the two inductors. If the element is pulsed again in the same direction, the persistent current does not change direction. If the element is pulsed in the reverse direction, the persistent current is reversed, and an output voltage can be observed either with a small secondary coil or by measuring the voltage directly across the large inductance.

The elements are extremely small, and it is reported that a packing value of 300,000 elements per cubic foot can be achieved.

**Conclusions**

The speed of operation of wire-wound circuits can be improved in many ways. A direct reduction in size would give an increase in speed which is inversely proportional to the square of the dimensions, but for the wire-wound device, any major improvement in this direction is limited by construction and handling difficulties. Superconductive alloys with resistivities higher than those of tantalum may be found for use as gate materials, but it is unlikely that an improvement of more than an order of magnitude would result from this alone. Where current gain is not required, gate wires of smaller diameter may be used, and an arbitrarily long section may be restored to the resistive state, thereby achieving an arbitrarily high switching speed.

For switches which must have current gain, however, if an improvement of more than perhaps two orders of magnitude is to be achieved, a reduction in physical dimensions is certainly necessary. For maximum switching speed it is clear that thin superconductive films offer the greatest possibilities. Switching speeds already observed for some of the persistent-current memory elements utilizing deposited films are of the order of 10 millimicrosecond.

Further development of deposited film techniques and devices should make the fabrication of extended and complicated circuitry a fairly straightforward matter. With the high speed and high density of logical elements which could result from this type of construction, it seems inevitable that superconductivity
will find practical applications to computer circuits.

References

6. The Peristatron, M. J. Buckingham, Ibid.
8. Ibid., p. 293.

Magnetic Switching

JAN A. RAJCHMAN
NONMEMBER AIEE

In the last decade, magnetic cores made of square hysteresis loop materials have become important in the manipulation of digital information. New materials, devices, circuits, and systems are still being discovered and invented at an unabated rate.

This paper attempts to bring to light some of the underlying philosophy of many devices and circuits employing cores by describing selected examples.

A core with hysteretic properties has an infinite number of possible remanent states and offers the possibility of storage of information by means of the value of flux at remanence. Cores which have a square hysteresis loop have, in addition, thresholds of current required for producing irreversible flux changes and clearly defined saturation limits of flux (Fig. 1). Therefore these cores can be used for switching as well as storage. There are current-driven magnetic circuits depending on the current thresholds, and voltage-driven circuits depending on the flux limits.

Cores Directly Driven by Electronic Devices

Cores are passive devices which in high-speed applications must be driven by active electronic devices, tubes, or transistors. Perhaps the simplest applications are those in which the cores are driven and sensed directly by electronic devices and do not drive each other. The current-coincident memory arrays and the combinatorial switches are the outstanding examples of such directly driven circuits. The selection system in memory arrays in which the magnetomotive force on the unselected cores is at most half that on the selected core is well known and will not be considered here.1,2

Combinatorial switches can be made to select one, or several outputs from a large group. This is accomplished by using a number of windings each linking certain cores in series in such a way that energizing selected groups of windings will produce an algebraic sum of magnetomotive forces which exceeds the threshold of switchover on the selected core only. There is a considerable difference between such switches and the current-coincident memory, which is also combinatorial, in that the nonselected cores in the switch can support arbitrarily large magnetomotive forces tending to drive them in the direction of their existing saturation, whereas this is not permissible in the memory arrays because the state of remanence is unknown by definition. Typical are the following types of combinatorial switches.

A switch to select one out of \( n \times m \) outputs by the choice of one input among \( n \), and one input among \( m \), can be made using an array of \( n \times m \) cores. The cores are linked by \( n \) rows and \( m \) columns and also by a common winding carrying a \( d-c \) biasing current.2 The input excitations switch over the selected core, and that core only, as one of the excitations neutralizes the \( d-c \) bias and the other produces the switchover. At the cessation of the selecting currents the \( d-c \) bias automatically restores the selected core. This feature is important since the two polarities of drive current always required in magnetic circuits are obtained without having to double the number of driving electronic circuits.

Another example is what might be called a combinatorial decoder switch.3 A typical case would be a switch with eight outputs and three inputs, whose purpose it is to select one output for every possible combination of inputs (Fig. 2). For simplicity, the cores are represented on the figure by heavy lines and the linking windings by 45 degree segments of line. The input signals are in pairs, each one linking half the cores. The first input links the cores by juxta­posed halves, the second by interlaced quarters and the third by interlaced eighths. The direction of winding is such that a current sent in one or the other branch of each input tends to magnetize the cores further into saturation. Consequently, the applications of the inputs have no effect per se. If during the presence of the inputs, all cores are energized in a direction tending to reverse their magnetization, only the core which is not inhibited by the input currents will have a net reversing magnetomotive force and therefore will be the only one to switch over. After the core has been switched, it can be restored by energizing a winding which links all cores. Decoding switches of this type have been used.

References

6. The Peristatron, M. J. Buckingham, Ibid.
8. Ibid., p. 293.