The Crossed-Film Cryotron and Its Application to Digital Computer Circuits

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INTRODUCTION

THE NAME *cryotron* was applied by the late D. A. Buck to the superconductive relay which he described.[1] Buck's cryotron consisted of a wire of tantalum surrounded by a coil of niobium and was operated at the boiling point of liquid helium at atmospheric pressure. At this temperature the tantalum "gate" wire was only just superconducting. By passing a sufficient current through the niobium control coil, a magnetic field was created which was sufficient to transform the tantalum gate to its resistive state.

It was found by two of the authors that it is possible to produce the cryotron in a geometry suitable for deposition on a flat surface.[2] This will be referred to as the crossed-film cryotron (CFC). The CFC was first presented in public at the Electron Device Research Conference at Ithaca in June 1959. Similar devices were described at the same meeting by M. L. Cohen, J. L. Miles, A. E. Slade and C. R. Smallman of the A. D. Little Company, and by A. E. Brenneman and R. de Lano of the IBM Research Center.

This paper describes a crossed-film cryotron deposited on an insulated superconductor. This CFC has a time constant of less than one microsecond and is approximately one hundred times faster than the original vacuum-deposited cryotron.[2] The d-c dissipation is less than 5 microwatts and the active area of each element is approximately 5×10^{-4} square centimeters. These cryotrons and all their interconnecting circuitry can be vacuum deposited at one and the same time in a few simple steps.

The cryotrons can be applied to both switching and storage. Some experimental storage and shift-register circuits are described, which demonstrate a circuit property unique to superconductors. A shift-register circuit is shown which is deposited in an area corresponding to 20,000 active elements per square foot.

Calculations are presented which show that with this component density, a computer or memory containing more than one million elements can be accommodated in a one-cubic-foot liquid helium container using presently available refrigeration methods.

SUPERCONDUCTIVE FILMS

The devices to be described are made up of tin, lead and insulator films only. Of these, only the tin films change their state during operation. We can, therefore, confine our attention mainly to tin films. At temperatures below the so-called critical temperature T_c, tin and lead become superconducting. For lead, $T_c = 7.2°K$. For the tin films used, $T_c \approx 3.75°K$. The devices described are operated at approximately 3.6°K. At this temperature, the tin films can readily be switched from the superconducting to the normal (resistive) state, but the lead films remain superconducting throughout.

Just as in the case of bulk materials, it is possible to restore a superconductive film to the normal state by the application of a magnetic field greater than the so-called critical field H_c. The variation of H_c for bulk tin is shown in the insert of Fig. 1.

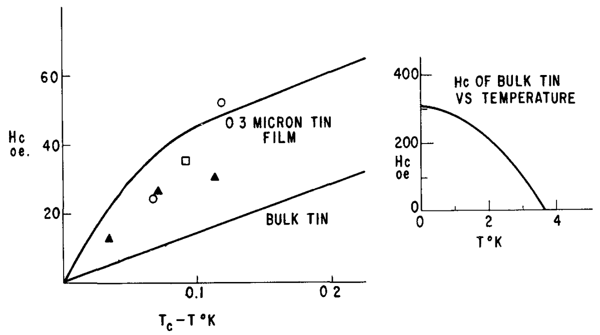

Fig. 1—Critical field of gate film as a function of temperature. Solid line: measured directly. Points: calculated from cryotron characteristics and grid widths, using Eq. 4. Grid widths: ▲ 16 microns (unshielded), □ 65 microns (shielded), ○ 40 microns (shielded).

The main portion of Fig. 1 compares H_c of bulk tin and H_c of a 0.3-micron-thick tin film. The film curve was determined experimentally, with a uniform magnetic field applied parallel to the film surface. The data points shown in the figure are values of H_c calculated from the electrical characteristics of crossed-film cryotrons. These are discussed in connection with Eq. (4) below.

Fig. 1 shows that H_c of the film is higher than for the bulk material. It can be established on the basis of thermodynamics[3] that if the film thickness is of the same order of magnitude as, or less than, the penetra-

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[1] D. A. Buck, "The Cryotron — A Superconductive Computer Component," *Proc. I.R.E.*, Vol. 44, pp. 482–493, 1956.

[2] V. L. Newhouse and J. W. Bremer, "High-Speed Superconductive Switching Element Suitable for Two-Dimensional Fabrication," *J.A.P.*, Vol. 30, p. 1458, Sept. 1959.

[3] D. Shoenberg, *Superconductiviiy*, pp. 171–174, 2nd edition, Cambridge Univ. Press, 1952.

tion depth, H_c varies inversely with film thickness. The penetration depth is roughly equal to the thickness of the surface layer in which the current flows in a bulk superconductor. For tin, the penetration depth at absolute zero is approximately 5×10^{-6} cm, but at temperatures close to T_c, it is larger. At 3.6°K, a typical operating temperature for a crossed-film cryotron, the penetration depth is about 0.1 micron.

The variation of resistance with current for a 0.3-micron tin film is shown in Fig. 2. By applying the current in short pulses, it is possible to obtain the so-called isothermal transition shown in the broken line. This curve is connected with the actual superconducting behavior of the film, and is reasonably independent of other film characteristics, such as resistivity, and of the substrate properties. If a *slowly*-rising current is passed through a film, Joule heating causes thermal "propagation" of resistive areas in the film.[4] This behavior is shown in the solid curve of Fig. 2, and is strongly dependent on substrate thermal conductivity and on film resistivity.

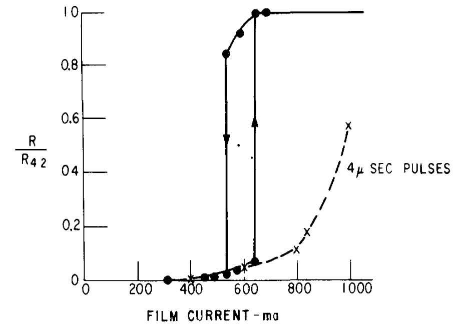

Fig. 2—D-c and pulse current-induced transitions for 0.3 micron thick, 4.05 mm wide tin film on sapphire substrate. ▲T = 0.08°K.

The current at which resistance first appears is known as the critical current I_c. For thin films $I_c = i_c W(T_c - T)$ where W is the film width and T the bath temperature, provided that $T_c - T \ll T_c$.[5] i_c increases as film thickness increases and appears to depend somewhat on heat treatment and film substrate. It has been found that i_c is more than doubled if the film in question is deposited on top of an insulated lead "shield" plane.

The explanation of why a tin film which lies adjacent to a lead shield plane has a higher critical current than a similar tin film deposited on glass is believed to be as follows: It can be shown[6] that a film in the shape of a cylinder will carry twice as much current as the same film unwrapped into a flat plate. When current passes through a tin film adjacent to a superconducting shield, surface currents are induced in the shield to prevent flux from penetrating into it. It can be shown that these surface currents double the field between the film and the shield, and produce an approximately zero field on the opposite side of the film. This field configuration is the same as would occur if the tin film were in the shape of a cylinder. It is to be expected, therefore, that the critical current for a shielded flat film is increased from the value for the unshielded flat film to that for the cylinder.

The mathematical problems of calculating the surface currents induced in a superconducting surface due to the presence of an external current-carrying conductor are similar to the problems of calculating the surface charge produced in a perfect conductor due to an external charge. It is found that some of the results of the "method of images" of electrostatics can be carried over to superconductors if an electronic dipole is replaced by a magnetic dipole, and a line of charge by a line of current. For a current-carrying wire above a superconducting surface, for instance, it can be shown that the net field outside the surface is equal to the field of the original current plus that of an equal and opposite shielding current which is the same distance behind the superconducting surface as the real current is in front. This effect increases the field between the current and the surface, but reduces it everywhere else. (It is assumed that the maximum net field is less than the critical field of the superconducting shield plane.) It can be seen therefore that if it is desired to reduce the effective inductance of a wire or length of film, it is simply necessary to place a superconducting plane with a high critical field in close proximity.

THE CROSSED-FILM CRYOTRON

The basic structure of a crossed-film cryotron (CFC) is shown in Fig. 3. If a sufficiently large current is passed through the "grid" film, the resulting magnetic field produces a resistive channel across the much wider tin "gate" film. The grid remains super-

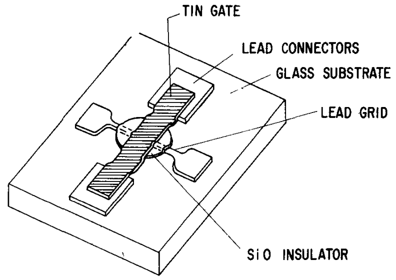

Fig. 3—Structure of crossed film cryotron. Typical dimensions: gate film – 0.3 microns × 2 mm, Insulator – 0.4 microns, grid film – 1 micron × 25 microns.

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[4] J. W. Bremer and V. L. Newhouse, "Thermal Propagation Effect in Thin Superconducting Films," *Phys. Rev. Letters*, Vol. 1, p. 282, 1958.

[5] J. W. Bremer and V. L. Newhouse, "On Current Transitions in Superconductive Tin Films," *Phys. Rev.*, to be published.

[6] V. L. Ginzburg, "Critical Currents in Superconducting Films," *Soviet Physics "Doklady,"* Vol. 3, p. 102, 1959.

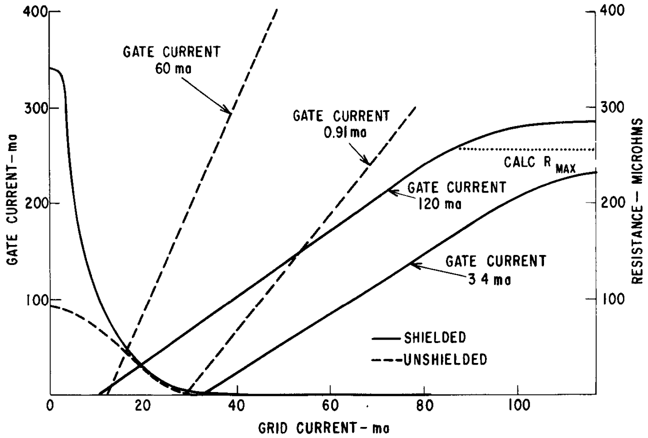

Fig. 4—Comparison of electrical characteristics of unshielded and shielded CFC. Shield insulation thickness = 4 microns. Grid width – 30 microns, gate width – 2 mm, $T_c - T = 0.07°K$.

conducting at all times. The characteristics of the unshielded cryotron are shown in the broken curves of Fig. 4. The curve intersecting the left-hand ordinate at 91 ma. shows values of gate and grid current at which resistance just begins to appear. Its intersection with the ordinate defines I_c for the gate film used. It can be seen that the presence of gate current "helps" the grid current to make the gate resistive.

The gain of the CFC can be defined as the ratio of the maximum current I_c which the gate can carry and remain superconductive, to the minimum grid current I_G required to make the gate resistive at low gate currents, *i.e.*,

$$g = I_c/I_G \tag{1}$$

For the unshielded cryotron $I_c = 91$ ma and $I_G = 31$ ma at the temperature shown. The other broken-line curves shown in Fig. 4 refer to the right-hand ordinate and represent the variation of resistance with grid current at constant gate current. The slope of these curves can be accounted for, to within a factor of 2, in terms of the known critical field of the film and the film resistivity.

If the CFC shown in Fig. 3 is covered with an insulating layer followed by a film of lead, the inductances of the gate and grid will be reduced as explained above, and the d-c characteristics will be somewhat changed as shown in the solid lines of Fig. 4. It can be seen that I_c for the shielded tin film is more than three times that for the unshielded film. I_G is also somewhat larger. However, the gain of the shielded cryotron is larger than that of the unshielded one.

It is noteworthy that the curves of resistance as a function of grid current for the shielded CFC approach a saturation value of resistance. This is because the field due to a grid above a shield plane falls off very rapidly beyond the edge of the grid; because in this region the fields, due to the grid current and the shield current, tend to cancel one another. It is to be expected, therefore, that the portion of the gate film which can be made resistive by grid current action is that portion lying under the grid. The maximum calculated resistance of the shielded CFC is shown dotted and is seen to be in fair agreement with experiment.

We will now show that the gain of the CFC is proportional to the ratio of the gate to the grid widths. As mentioned above, for thin tin films, I_c is proportional to the film width W, *i.e.*,

$$I_c = i_c W \,. \tag{2}$$

Here i_c is a constant of the material roughly proportional to $T_c - T$ as long as this is small.

In a current-carrying superconducting film (at least when the film thickness is large compared to the penetration depth of the current), the current density is not uniform over the film surface, but is more concentrated near the edges. For a current-carrying film close to a superconducting shield plane, however, the current is distributed more uniformly.

The field H between a film of width w carrying a current I which is assumed distributed uniformly, and a shield plane is

$$H \approx 0.4\pi I/w \,. \tag{3}$$

This formula will apply to the field in the space between a grid and its shield plane, which contains the gate film. If the gate film has a critical field H_c at which it becomes resistive, then the grid current I_G at which the gate just becomes resistive will, using Eq. (3), be

$$I_G \approx H_c w/0.4\pi \,. \tag{4}$$

The points shown in Fig. 1 are values of H_c calculated from experimental values of I_G for representative cryotrons of different grid widths. It is clear that Eq. (4) is at least approximately correct. From (1), (2) and (4) we finally obtain the gain as

$$g = 0.4\pi \frac{i_c}{H_c} \frac{W}{w} \,. \tag{5}$$

It is seen that the gain is proportional to W/w. i_c/H_c is a property of the material and decreases with gate film thickness. i_c rises linearly with $\Delta T = T_c - T$ close to the critical temperature. However, as Fig. 1 shows, the curve of H_c vs. ΔT has a knee at $\Delta T \leq 0.08°K$. It is to be expected, therefore, that g should rise strongly as the temperature is decreased below T_c until T goes below the knee of the H_c-vs.-ΔT curve. This appears to be the case. The cryotrons described here are operated at $\Delta T = 0.07°K$, *i.e.*, just above the "knee" and are not, therefore, operating at their maximum gain.

The speed of a cryotron is, of course, dependent on the mode of operation. In the circuits described below, the cryotron gate is in parallel with the load, which consists of the grid crossing a similar cryotron. The time constant τ at which current will be diverted from a cryotron gate to the grid of the load cryotron is L/R where R is the resistance of the driving cryotron. L is the sum of the grid inductance of the driven cryotron, the gate inductance of the driving cryotron, and the inductance of the connecting circuits. Out of all these terms, only the grid inductance is important.

The inductance of a grid of width w spaced d cm from the superconducting shield plane can be shown to be $4\pi \times 10^{-9}\, d/w$ henries/cm. The driven cryotron has a width W, hence its grid has a length W and

$$L = 4\pi \frac{Wd}{w} \times 10^{-9} \text{ henries.} \tag{6}$$

As discussed in connection with Fig. 4, the maximum portion of a shielded cryotron which becomes resistive is that part of the gate film covered by the grid. Hence, the resistance R of the driving cryotron of width W, energized by a grid of width w, is

$$R = \rho \frac{w}{Wt} \text{ ohms} \tag{7}$$

where t is the gate film thickness and ρ the effective bulk resistivity. (For very pure films, ρ is itself a function of t, but for the relatively impure films used here, this dependence can be neglected.)

From (6) and (7), we find that the effective time constant τ of one cryotron driving another is

$$\begin{aligned} \tau &= L/R \\ &= 4\pi \frac{td}{\rho} \left(\frac{W}{w}\right)^2 \times 10^{-9} \text{ sec.} \end{aligned} \tag{8}$$

Substituting from (5) for W/w in (8) we find the time constant in terms of the gain:

$$\tau = 4\pi \frac{td}{\rho} \left(\frac{H_c}{0.4\pi i_c}\right)^2 g^2 \times 10^{-9} \text{ sec.} \tag{9}$$

There are two points of interest in (9). First, $\tau \propto t(H_c/0.4\pi i_c)^2$. This shows that there is an optimum value of the gate thickness t, because as we attempt to reduce τ by reducing t, $H_c/0.4\pi i_c$ increases. For solid wires, $H_c/0.4\pi i_c \rightarrow 1$, but for the 0.3-micron tin films presently used, $H_c/0.4\pi i_c$ is between 20 and 50. The second point of interest is that τ is not a function of the grid and gate widths. Hence, a reduction in cryotron area will not increase speed.

Present values for the material constants in (9) are

$$t \approx 0.3 \text{ microns}, \qquad \rho \approx 6\text{–}12 \times 10^{-7} \text{ ohm-cm},$$

$$d \approx 1.0 \text{ micron}, \qquad \frac{H_c}{0.4\pi i_c} = 20\text{–}50.$$

A practical value for the gain is 2. Substituting these values into (8), we obtain a theoretical range of $\tau = 5 - 65 \times 10^{-8}$ sec. A typical cryotron, described below, has an experimental time constant of 38×10^{-8} sec. at the temperature of operation.

A Simple Storage Circuit

We will now describe a simple storage circuit which makes use of a principle unique to superconducting networks. The principle will be illustrated with the circuit shown in Fig. 5-A.

In one mode of operation of this circuit, a current is applied between X and Z. Most of this flows through the path XZ rather than XYZ, because the former has much lower inductance. The equivalent circuit is shown in Fig. 5-B.

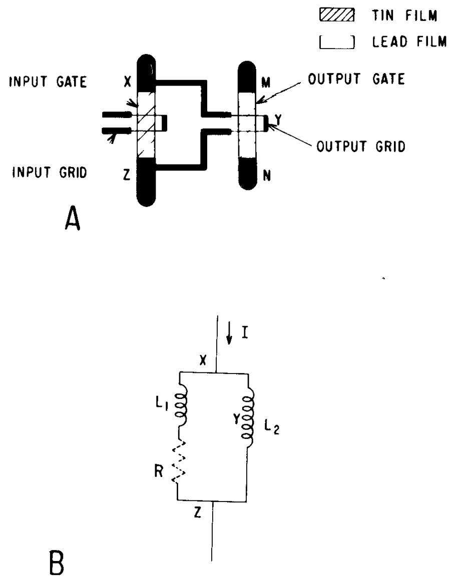

Fig. 5—(a) Cryotron storage cell. (b) Equivalent circuit.

If current is now passed through the input grid, XZ becomes resistive and I is diverted through the path XYZ. It is now possible to switch off the current through the input grid so that XZ becomes superconducting again. Since L_2 is still superconducting, it is to be expected that I will remain diverted through L_2, even though L_1 has become superconducting again. This does, in fact, happen experimentally. The current in XYZ can conveniently be determined with a d-c measurement by measuring the resistance of MN.

If, after I has been diverted to L_2 and after L_1 has become superconducting again, I is switched off, a circulating current will remain in loop XYZ. Its magnitude can be calculated as follows:

Assume that a current $+I$ has been injected into node X and completely diverted to L_2, through L_1's having been temporarily been made resistive. If now current $-I$ is injected into node X, it will divide itself between XZ and XYZ in the inverse ratio of their inductances. The current along XZ will be

$$I_{XZ} = -I \frac{L_2}{L_1 + L_2},$$

and the net current along XYZ will be

$$I_{XYZ} = I - I \frac{L_1}{L_1 + L_2} = I \frac{L_2}{L_1 + L_2}.$$

Therefore, $-I_{XZ} = I_{XYZ}$. Hence, the circulating current

$$I_{circ} = \frac{L_2}{L_1 + L_2} I. \tag{10}$$

Eq. (10) has been confirmed experimentally, and currents have been stored for several hours.

The results which have been described in connection with the above storage circuit can be generalized. If a current is injected into a network of superconductive elements, it will distribute itself among them in inverse ratio to their inductances. By making one or more of these inductors resistive for various lengths of time, current will be diverted from the resistive elements to the superconducting ones. As soon as the resistive elements are made superconducting again, however, the current distribution stops changing, as long as the external injected current remains constant.

It is clear that in a cryotron computer, analog and digital storage will be simpler than in a transistor computer, where positive feedback circuits, or magnetic cores which cannot conveniently supply a continuous output, are required.

The circuit of Fig. 5 provides a convenient way of measuring the effective speed of the cryotrons used in it. The deflection of current from leg XZ to leg XYZ takes place with a time constant

$$\tau = (L_1 + L_2)/R \tag{11}$$

(R is the resistance produced in XZ by the input grid current). By applying individual pulses of known length to the input grid, we can measure the current changes in the output grid and obtain an experimental value for τ.

The result of applying 0.05-microsecond current pulses to the input grid of one of the storage loops shown in Fig. 7 is shown in Fig. 6. The experimental curves have a time constant of approximately 0.38 microseconds. The value given by Eq. (11), using calculated values for $L_1 + L_2$ and experimental values for R, is 0.33 microseconds. The curve of rising current is obtained when 150 ma. is injected into the cryotron loop and gradually diverted to the output leg. The curve of decreasing current corresponds to a stored current (with the external current switched off) being destroyed by pulses on the input grid.

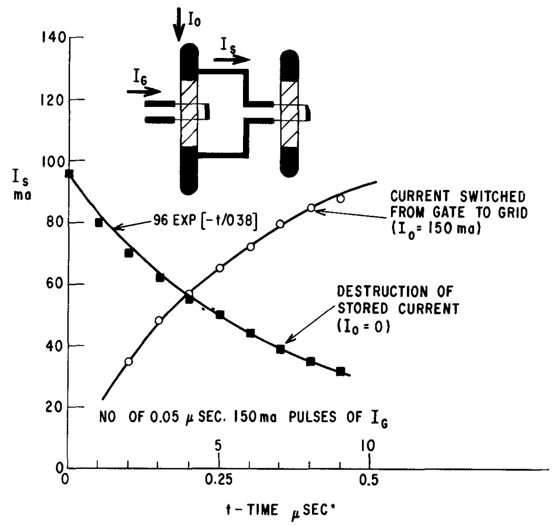

Fig. 6—Change of stored current due to 0.05 μsec pulses on input grid of storage cell of Fig. 7. Curves are fitted to the data points corresponding to a time constant of 0.38 μsec.

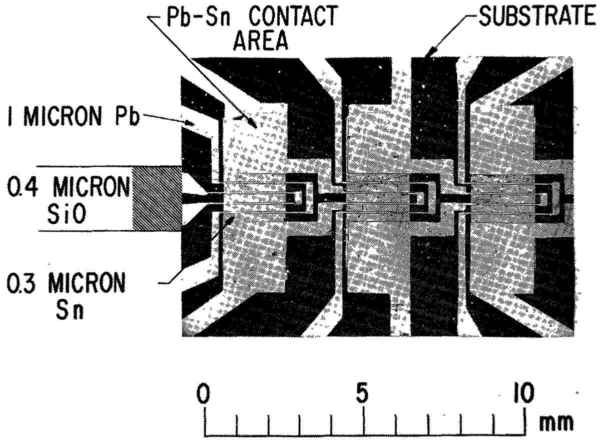

Fig. 7—Portion of experimental shift register. Note the insulator film separating the grids from the underlying gate films.

A Shift Register

The memory circuit described has been applied to a shift register. A short portion of such a register is shown in Fig. 7. The register is of the three-stages-per-bit type and requires two advance and two reset windings. A diagram and a set of calculated waveforms are shown in Fig. 8.

Information travels from left to right. To inject a "1" into the register, the input winding is pulsed while advance current I_1 is on. This diverts I_1 from the first cryotron to its output grid and when I_1 goes off, a circulating current C_1 remains in the first cell. I_2 is now injected into the second storage cell. Due to the existence of C_1, I_2 will be diverted to the output grid of the second storage cell. It is necessary at this time to destroy C_1. This is done by passing current through the reset winding R_2. C_1 has to be destroyed before I_2 is switched off since, otherwise, C_2, the circulating current in the second storage cell

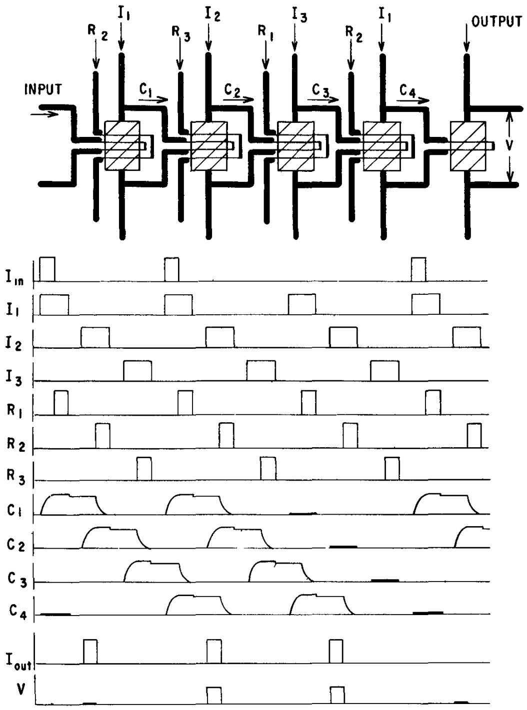

Fig. 8—Calculated waveforms for shift register.

caused by the effect of C_1 on I_2, would be destroyed. After C_1 has been destroyed and I_2 switched off, the injected "1" is represented by the circulating current C_2 in cell 2. In similar fashion, C_3 is created and C_2 is destroyed. Only now can a new "1" be injected into the first storage cell. The grid of the last storage cell crosses an output cryotron whose resistance is an indication of the presence or absence of the circulating current C_4. As described earlier, the experimental and calculated time constant of the cryotron in this circuit module is 0.38 microseconds. This time constant could probably be reduced to approximately 0.1 microsecond by working at a lower temperature and changing the cryotron dimensions to lower the gain. The register has been used to transfer information. However, it has not yet been operated at high repetition rates.

A summary of cryotron characteristics is shown in the table:

Time	0.4 μsec
Size	6 mm^2
Dissipation (d-c)	$= 5 \times 10^{-6}$ watts

The lower limit in size is presently set by difficulties in getting good contact between the CFC gate and its connecting circuitry.

Using our present elements and putting one per square cm (this would leave plenty of area for interconnections), it should be possible to accommodate 1000 circuits on a 1 ft^2 plate. Stacking two of these plates per cm would give a 50,000 element computer in 1 cu ft. Assuming each element to be on for 10 per cent of the time gives the total dissipation as $5 \times 10^4 \times 5 \times 10^{-7} = 0.025$ w. Approximately 0.25w of heat enters the liquid helium due to radiation and conduction through the container. It has been calculated that 100 input and output leads, 10 of which carry 200 ma. dc, would contribute less than 0.2w in conduction and Joule heating. (It was assumed that the upper ends of these leads would be in thermal contact with a liquid nitrogen chamber.) The total heat inflow is therefore just under 0.5w for the system under discussion. Helium refrigerators with 1-w capacity for a 1-cu.-ft. volume are presently being designed.

What role will cryotrons play in future computers? They are, of course, small. They appear to constitute the cheapest method of assembling a large number of circuits in a small place, and they are the only active circuit component which can be deposited in a few steps at the same time as the interconnections.

Because CFC's are, in principle, as cheap as magnetic cores, they make possible radically improved memory structures where each storage element can have logic associated with it. Memories, in fact, appear as an attractive first application because their structure is repetitive and because they have many less logic levels than even the simplest computer.

Computers are presently built from plug-in circuit packages where each plug-in unit represents a few logical elements. CFC's make it possible to deposit the equivalent of a present-day rack on a small plate in a few hours. The problems of testing and fault correction in such a complex multi-level logic module are real, but they are not greater for cryotrons than for any other component which would allow similar packing densities. If these problems can be solved economically, and we feel sure that they can be, the next ten years may see the development of cryotron ground-based computers, as well as air-borne computers and memory sustems.

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