Nov. 1, 1960 H. O. McMAHON 2,958,836

MULTIPLE-CHARACTERISTIC SUPERCONDUCTIVE WIRE

Filed July 11, 1957 2 Sheets-Sheet 1

FIG. 1

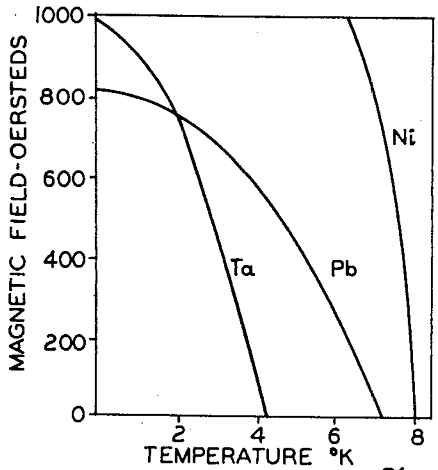

FIG. 2

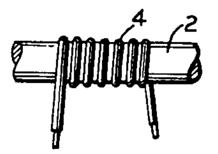

FIG. 3

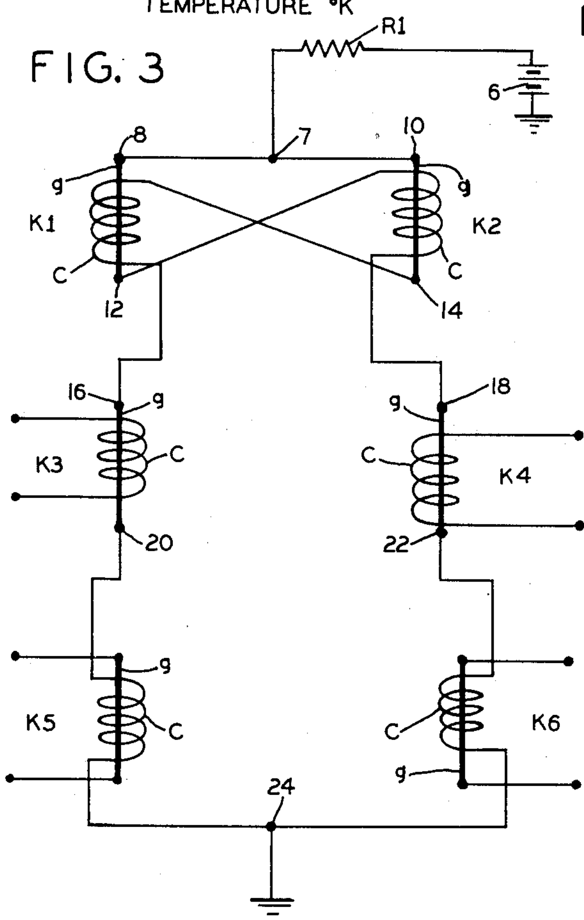

FIG. 4

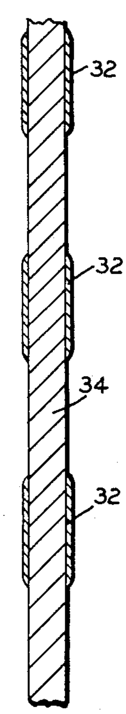

FIG. 5

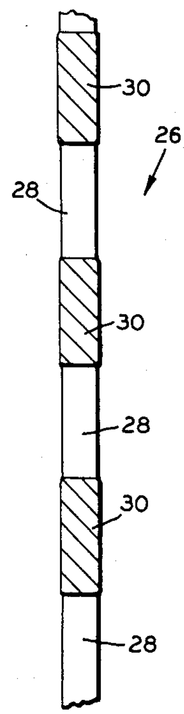

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FIG. 7

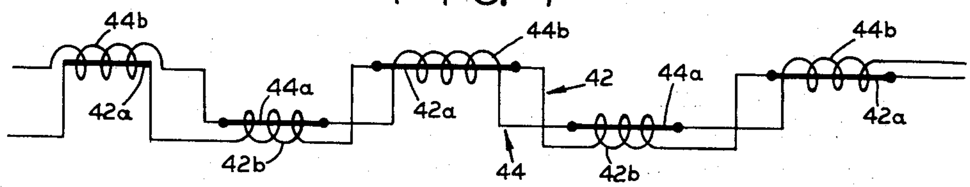


FIG. 8

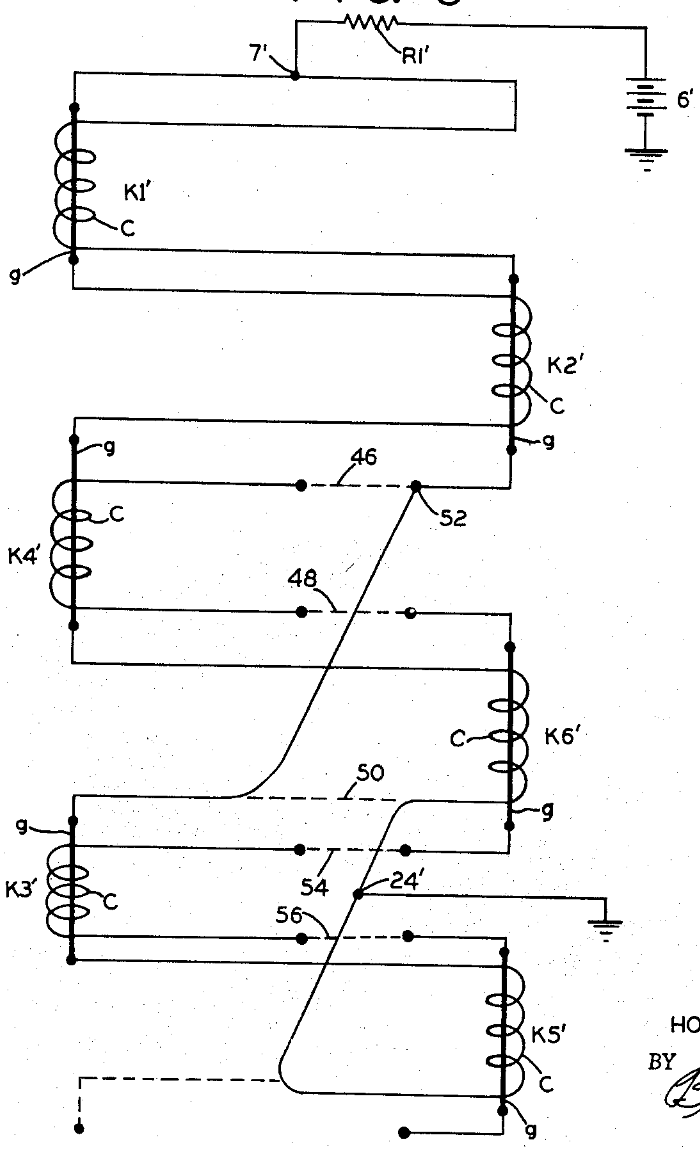
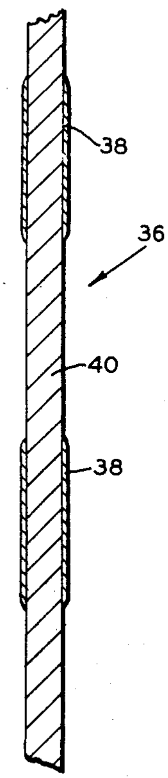


FIG. 6



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MULTIPLE-CHARACTERISTIC SUPERCONDUCTIVE WIRE

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8 Claims. (Cl. 338—32)

This invention relates to an improved construction for cryotron circuits. More particularly, it relates to, as an article of manufacture, a conductor having zones of different superconductive properties formed along its length and to constructions utilizing conductors of this type to form cryotron circuits. For example, such a conductor may be intertwined with a second similar conductor to form a plurality of connected cryotrons.

My improved construction may best be understood from the following description taken in connection with the accompanying drawings in which:

Figure 1 is a family of curves for different materials showing how the temperature at which a material becomes superconductive changes as a function of applied magnetic field, the materials being superconductive when maintained under the conditions represented by the areas to the left of and below the respective curves.

Figure 2 is a diagrammatic representation of a cryotron,

Figure 3 is a schematic drawing of a cryotron flip-flop circuit made from cryotrons of the type illustrated in Figure 2,

Figure 4 is a section through a base conductor having a coating of different superconductive properties deposited on portions thereof,

Figure 5 is a section through the conductor of Figure 4 with the coating diffused into the conductor to form a composite cryotron conductor made according to my invention,

Figure 6 is a sectional view of another embodiment of a composite cryotron conductor made according to my invention,

Figure 7 is a diagrammatic representation illustrating how a plurality of connected cryotrons may be formed from conductors of the type illustrated in Figures 3 and 4, and

Figure 8 is a schematic diagram of the cryotron flip-flop circuit of Figure 3 fabricated from a plurality of cryotrons arranged as in Figure 7.

Similar reference characters refer to similar parts throughout the several views of the drawings.

The cryotron, which is a switching element useful in digital computers, depends for its operation on the changes in properties of certain electrical conductors when subjected to temperatures approaching absolute zero. As the temperature approaches absolute zero, in the absence of a magnetic field, these materials change suddenly from a resistive state to a superconductive state in which their resistance is identically zero. The temperature at which this change occurs is known as the transition temperature. When a magnetic field is applied to the conductor, the transition temperature is lowered, the relationship between applied magnetic field and transition temperature for a number of these materials being shown in Figure 1. As shown in this figure, in the absence of a magnetic field tantalum loses all electrical resistance when reduced to a temperature of 4.4° K. or below, lead does so at 7.2° K., and niobium at 8° K.

In all, there are twenty-one elements, in addition to many alloys and compounds, which undergo transition to the super-conductive state at temperatures ranging between 0 and 17° K. The presence of a magnetic field causes the transition temperature to move to a lower value, or, if a constant temperature is maintained, an increase in the magnetic field to a certain level will cause the superconductive material to revert to its normal resistive state. From Figure 1 it is apparent that a magnetic field of between 50 and 100 oersteds will cause a tantalum wire held at 4.2° K. (the boiling point of liquid helium at atmospheric pressure) to change from the superconductive to the resistive state.

The cryotron is a circuit element which makes use of the shift between the superconductive and resistive states of these materials when held at constant temperatures. For example, Figure 2 illustrates a cryotron having a central or gate conductor **2** about which is wound a control coil **4**, both the gate conductor and the coil being of materials which are normally super-conductive at depressed temperatures. The entire unit is immersed in liquid helium to render the gate conductor **2** and the control conductor **4** superconductive. If a current of sufficient magnitude is applied to the control conductor, the magnetic field produced thereby causes the gate conductor to transfer from the superconductive to the resistive state. Thus, the control coil and gate wire form an electrically-operated switch in which the gate can be changed from the superconductive to the resistive state by the application of current to the control coil.

Tantalum is a desirable material for gate conductors, since its transition temperature in the 50-to-100-oersted region is 4.20 K, the boiling point of helium at a pressure of one atmosphere. This temperature is attainable without the use of complicated pressure or vacuum equipment for raising or lowering the temperature of helium. Niobium, which has a relatively high quenching field (the field strength required to render a super-conductive material resistive), is usually used as the material for the control coil, since it is desirable, and in many cases necessary, that the control conductor remain superconductive throughout the operation of the cryotron, and this coil is subject to substantially the same magnetic fields as those imposed on the gate conductor. Additionally, in most applications it is desirable to have the control conductor in the form of a coil such as coil **4** in Figure 2 in order to minimize the current necessary to produce a quenching field.

In cryotron circuitry, the gate conductor of one cryotron is often connected in series with the control conductor of another, and therefore the cryotron must provide a current gain for successful operation of the circuit, i.e. the current controlled by the gate conductor of the cryotron should be larger than that required to energize its control coil. If the control conductor is not in the form of a coil, the current through the conductor required to quench the tantalum gate may produce a field large enough to cause self-quenching of a tantalum gate connected in series with it. In practice it has been found that suitable current gain is obtained in a cryotron having a .009 inch tantalum gate conductor with a single layer control coil of .003 inch niobium wire having 250 turns per inch.

A simple bi-stable element, the basic unit of a binary digital computer, may be formed with cryotrons by connecting the gates of two of the units in parallel and arranging to have one gate or the other conduct all the current through the combination in the same manner as a vacuum tube flip-flop. Thus, as shown in Figure 3, a cryotron flip-flop may comprise two cryotrons **K1** and **K2** whose gate conductors **K1*g*** and **K2*g*** are connected together at one end to a power supply, illustratively shown as a battery 6, in series with a limiting resistor R1. Preferably, resistor R1 is of much higher resistance than the flip-flop circuit, so that the power supply is essentially a constant current source. Gate conductor K1*g* is connected in series with control coil K2*c*, and gate conductor K2*g* is similarly connected to control coil K1*c*. The control conductors are returned to ground to complete the circuit through read-in cryotrons K3 and K4, respectively, and read-out cryotrons K5 and K6, respectively, in a manner to be described. When conductor K1*g* is resistive and conductor K2*g* is superconductive, an entirely superconductive path is formed through gate conductors K2*g* and K3*g* and control conductors K1*c* and K5*c*. The path through the series combination including conductor K1*g* is resistive at this time. Thus, all the current from the power supply will flow through gate conductor K2*g* and none through conductor K1*g*, and this same current flowing through control coil K1*c* will keep the gate conductor K1*g* enclosed therein in the resistive state. The flip-flop is thus stable in this position, much as a conventional bi-stable vacuum tube flip-flop is stable in one position or the other. If the available current from the power supply is less than twice that required to quench one of the gate conductors, and if a pulse is applied to control winding K3*c* to quench gate conductor K3*g* to make the path including conductor K2*g* resistive, the current divides approximately equally between the two paths. There is now insufficient current flow through control conductor K1*c* to maintain the gate conductor K1*g* in its resistive state. As gate conductor K1*g* changes from the resistive to the superconductive state, a superconductive path is formed through it and control conductor K2*c*, gate conductor K4*g*, and control conductor K6*c*; thus, all the available current flows through this path to quench gate conductor K2*g*. The flip-flop thus reaches its other stable position.

Similarly, a current pulse of sufficient magnitude, applied to control conductor K4*c*, will cause the flip-flop to revert to the former position. Gate conductor K5*g* or K6*g* will be quenched, depending on whether the superconductive path through the flip-flop is through control conductor K5*c* or K6*c*, and therefore the conductive states of these gate conductors are indicative of the position of the K1—K2 flip-flop.

Because of its small size and low cost, the cryotron is an ideal basic switching element for use in large data processing equipment, which may utilize many thousands of such elements, connected together in a number of basic circuits, such as the flip-flop illustrated in Figure 3. Prior to my invention, the small size of the individual cryotron, in most respects an important advantage, has presented a serious problem in the fabrication of the various circuits in which it is employed. The four terminals of each cryotron are generally connected to other superconductive circuit elements by welding, to preserve superconductivity at the point of connection, and thus cryotron circuits require an average of approximately two welded joints per cryotron, e.g. the flip-flop of Figure 3 has ten internal welded connections, as indicated by the reference characters 7 through 24. The individual gate and control conductors of the cryotrons may be as small as one or two mils in diameter, and, therefore, extreme care must be used in handling these elements and forming the welded connections between them, in order to prevent breakage and to assure correct connection. In fact, the fabrication of cryotron circuits is generally performed under a microscope and is a time-consuming, tedious job.

Accordingly, it is a principal object of my invention to provide an improved cryotron circuit construction having a minimum of internal connections, and cryotron gate and control conductors adapted for efficient use in such construction. It is another object of my invention to provide a cryotron circuit construction of the above character whose assembly requires minimum handling of individual cryotrons. It is a further object of my invention to provide cryotron conductors of the above character capable of use in mechanized assembly operations. It is yet another object of my invention to provide cryotron conductors of the above character susceptible of low-cost manufacture. It is a still further object to provide a cryotron flip-flop using a circuit construction of the above character. Other objects of my invention will in part be obvious and in part appear hereinafter.

The invention accordingly comprises an article of manufacture and the features of construction, combinations of elements, and arrangements of parts which will be exemplified in the constructions hereinafter set forth, and the scope of the invention will be indicated in the claims.

In general, my invention utilizes composite superconductive wires having alternate gate and control portions which require different magnetic field strengths to render them resistive at the temperature of operation. Thus, a conductor made according to my invention may have a gate segment with a relatively low quenching field followed by a control segment with a relatively high quenching field, in turn followed by a second gate segment, and so on. A conductor having many such segments may be cut according to the number of cryotrons to be made from it and the manner in which they are to be interconnected.

Accordingly, one composite conductor having two gate and two control segments might be substituted for gate K1*g*, control coil K2*c*, gate K4*g*, and control K6*c* in Figure 3; similarly, a conductor of this type might be substituted for the other gate and control conductors. The two composite conductors would be connected together at 7 and 24, and thus the number of internal connections in Figure 3 would be reduced to two, 20 percent of the number previously required.

My composite cryotron conductor may comprise a tantalum wire having niobium-coated portions, with the uncoated portions serving as gate segments and the coated ones, which have a substantially greater quenching field, serving as control segments. Alternatively, a wire having a base material with a given superconductive property may have another material diffused into it along alternate segments to alter the properties of those segments so that the treated and untreated portions have different quenching field strengths.

In Figure 5 I have illustrated a composite cryotron conductor made according to my invention. As shown therein, a conductor, generally indicated at 26, comprises alternate control segments 28 of niobium and gate segments 30 of a niobium-tantalum alloy. The conductor 26 may be made, as illustrated in Figure 4, by first forming coatings 32 of tantalum at spaced intervals along a niobium wire 34. The coatings 32 may be formed by any desirable process such as evaporation, electro-deposition, etc. The coated wire is then heated at a suitable temperature for a sufficient period of time to diffuse the tantalum coatings into the niobium base conductor. This results in the composite conductor 26 of Figure 5, in which the untreated niobium segments 28 have control conductor characteristics, i.e. stronger quenching fields, and the segments 30 of the niobium-tantalum alloy have gate characteristics, i.e. weaker quenching fields.

Another composite cryotron conductor embodying the features of my invention is illustrated in Figure 6. As shown therein, a conductor, generally indicated at 36, comprises a tantalum base conductor having niobium-coated control segments 38 and uncoated tantalum gate segments 40. The niobium coatings may be formed by evaporation or electro-deposition in similar fashion to the coatings 32 of Figure 4.

Conductors 26 and 36 are preferably as small in diameter as possible, the lower size limit being determined mainly by problems in handling. Thus the base conductors 34 and 40 are preferably five-mil wires, with the untreated segments of the finished composite conductors having the same diameter; the treated segments **30** and **38** may have somewhat greater diameters, resulting from the introduction of additional material into them. The tantalum coatings **32** of Figure 4 should be thick enough to provide segments **30** having quenching characteristics sufficiently different from those of the niobium control segments **28** to provide efficient circuit operation, i.e. the disparity in quenching fields between the segments **28** and **30** should be at least 3 to 1. The niobium coatings on the segments **38** should be thick enough to insure complete coverage of the portions of the base conductor beneath.

While the conductors **26** and **36** have been described using niobium and tantalum, it will be understood that other materials may be provided if they have widely different quenching characteristics, to insure that, in circuit operation, the control segments will remain superconductive during the quenching of the gate segments associated with them. It will also be understood that composite conductors having segments of more than two quenching characteristics may be provided within the purview of my invention. Thus, a conductor similar to the conductor **36** may be formed with lead-coated segments in addition to the niobium-coated and untreated tantalum segments. The tantalum segments would be quenched by relatively low quenching fields, the lead-coated segments by stronger fields, and the niobium-coated ones by still stronger fields.

My composite superconductive wire may be used to form a plurality of connected cryotrons, as illustrated in Figure 7. As shown therein, composite conductors **42** and **44** have gate and control segments **42*a*** and **42*b***, and **44*a*** and **44*b***, respectively. The conductors may be of the type illustrated in Figures 5 or 6, and they are preferably wound by suitable machinery to form a stock material having any desirable number of sections, each section being an individual cryotron, with a control segment of one conductor formed into a coil around a corresponding gate segment of the other conductor. Portions of the control segments are also used as the connecting wires between the sections, so that in subsequent use these connecting wires will remain superconductive throughout the operation of the circuit in which they are incorporated.

The superconductive stock serves as a convenient material for the fabrication of all types of cryotron circuits, including elementary cryotron switches as well as the most complex circuits. Thus, as will be described, a piece of stock of the right length may be cut off and various operations may be performed on it to form a cryotron flip-flop. It will be noted that, while the lengths of the various segments may vary, in general, it is desirable that all the segments of each quenching characteristic be of equal length to facilitate the formation of the stock.

In Figure 8 I have illustrated a flip-flop made from the cryotron stock of Figure 7. Six cryotrons are detached from the stock as a single unit, the cryotrons serving as K1′, K2′, K3′, K4′, K5′, and K6′ in Figure 8. The conductors are welded together at one end to form a connection **7′** similar to connection **7** and are connected through a resistor R1′ to a battery **6′**. Proceeding downwardly (Figure 8) from connection **7′**, cryotrons K1′ and K2′ are connected with the control coil of each in series with the gate of the other, as in Figure 3. At cryotron K4′, however, the stock is altered by cutting, as indicated by the dotted lines **46** and **48**, to isolate the control coil K4′*c*, whose terminals then serve as read-in terminals. Gate K4′*g* remains in series with gate K1′*g* as in Figure 3. The connection between gate K3′*g* and control coil K6′*c* is severed as indicated at **50**, and the gate is connected in series with gate K2′*g* by a welded connection **52**. Control coil K3′*c* is isolated from gates K5′*g* and K6′*g*, as indicated by the dotted lines **54** and **56**, and cryotron K3′ thus serves as the other read-in cryotron. Gate K6′*g*, isolated at **48** and **54**, and gate K5′*g*, isolated at **56**, may thus serve as read-out gates, their control coils K6′*c* and K5′*c* being in series with read-in gates K4′*g* and K3′*g*, respectively. The control coils K5′*c* and K6′*c* are also connected together at a welded junction **24′** similar to junction **24** of Figure 3.

Thus, the elements of Figure 8 are connected in the same circuit relationship as are their counterparts in Figure 3, and the operation of the two circuits is identical. However, only three internal connections are required in the construction of Figure 8, as compared with the ten which are required when the circuit is constructed from individual cryotrons.

Thus I have described a composite cryotron conductor having segments with different quenching characteristics. Segments along the same conductor may thus serve as gate and control elements in various superconductive circuits, thereby eliminating many of the welded connections between gate and control elements heretofore required in the fabrication of such circuits. These composite superconductive conductors may be manufactured in any suitable fashion, and I have illustrated two forms which they may take, although others may also be found suitable.

I have also described a cryotron stock formed from a pair of composite conductors. The superconductive stock shown is very useful in such cryotron applications as flip-flops, and I have illustrated a simple flip-flop in which the number of internal welded connections is reduced from ten to three through the use of this stock. Although the above description is specifically directed to stock comprising two composite conductors, it will be noted that three or more such conductors, with segments having any desirable number of quenching field values, may be combined in a similar manner for various circuit applications.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above article and constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

I claim:

1. As an article of manufacture, a conductor for use in the manufacture of the combination of superconductive electric circuit elements and means for maintaining a low temperature environment therefor, said conductor being superconductive in said environment in the absence of an applied magnetic field and having gate portions requiring a given magnetic field strength to be rendered resistive and control portions requiring a greater magnetic field strength to be rendered resistive, said gate and control portions being periodically disposed along the length of said conductor in end-to-end electrical superconducting relationship.

2. The combination defined in claim 1 in which said gate segments are of a niobium-tantalum alloy and said control segments are of niobium.

3. As an article of manufacture, a conductor for use in the manufacture of the combination of superconductive electric circuit elements and means for maintaining a low temperature environment therefor, said conductor being superconductive in said environment in the absence of an applied magnetic field and comprising a base conductor requiring a given magnetic field strength to be rendered resistive, said base conductor having formed on its periphery at spaced intervals along its

length coatings of a material requiring a different magnetic field strength to be rendered resistive, the ends of each of said coatings being in electrical superconductive relationship to said base conductor.

4. The combination defined in claim 3 in which said base conductor is of tantalum and said coatings are niobium.

5. As an article of manufacture, a conductor for use in the fabrication of the combination of superconductive electric circuit elements and means for maintaining a low temperature environment therefor, said conductor being superconductive in said environment in the absence of an applied magnetic field and having a set of first portions requiring a given magnetic field strength to be rendered resistive and a set of second portions requiring a greater magnetic field strength to be rendered resistive, said first and second portions being alternately disposed along the length of said conductor in end-to-end superconducting relationship, one of said sets of portions being of a material having one of said field strengths and the other of said sets of portions being of an alloy including said material and a material having a different quenching field strength.

6. As an article of manufacture, cryotron stock for use in the fabrication of the combination of superconductive electric circuit elements and means for maintaining a low temperature environment therefor, said stock

comprising a pair of conductors, each of which is superconductive in said environment in the absence of an applied magnetic field, said conductors each having a central base portion with a given magnetic field strength and a plurality of spaced coatings disposed along said base portion, said coatings being of a material having a greater magnetic quenching field strength than said base portion, the ends of said coatings being in electrical superconductive relationship with said base portion, the coated portions of each conductor being in the form of coils wound about the uncoated portions of the other conductor.

7. The combination defined in claim 6 in which said base portions are of tantalum and said coatings are of niobium.

8. The combination defined in claim 6 in which said coated and uncoated portions are periodically disposed along said conductors.

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