ABSTRACT

A method for manufacturing a high Tc superconducting circuit elements is disclosed, which comprises the steps of preparing a single crystal conductive substrate of Sr$_2$RuO$_4$ by a floating zone melting process; epitaxially growing on the (001)-surface of the Sr$_2$RuO$_4$ substrate a high Tc copper oxide-based superconducting film with a thickness of 1 to 1000 nm; depositing metal pads onto said superconducting film to form electrical contacts; and applying a metal pad to the surface of the substrate to form an electrical contact.

10 Claims, 2 Drawing Sheets
METHOD FOR MANUFACTURING HIGH Tc SUPERCONDUCTING CIRCUIT ELEMENTS WITH METALLIC SUBSTRATE

This is a division of application Ser. No. 07/843,880, filed Feb. 27, 1992 now U.S. Pat. No. 5,266,558.

BACKGROUND

This invention relates to superconducting circuit elements, namely heterostructures such as SNS Josephson junctions and field-effect transistors, having a sandwich structure consisting of at least one layer of high-Tc superconductor material arranged adjacent to a metallic substrate, having an insulating layer interposed between the high Tc material and the metallic substrate. Both the substrate and the insulator consist of materials having structural properties sufficiently similar to those of the superconductor so that mechanical and chemical compatibility is guaranteed.

For device applications of high-Tc superconductors, it is desirable to find electrically conductive materials, in particular metals, which are compatible with the high-Tc superconductor materials. Compatibility in this context means a best possible match of the respective lattice constants, and the absence of deleterious diffusion effects at the interfaces of the materials involved. These materials may be used, for example in thin film form for SNS heterostructures (where S stands for superconductor, and N stands for normal metal), or they may serve as the bulk substrate in a field-effect transistor among other applications.

An European application EP-A-0 409 338 discloses a planar Josephson device of the type where at least one layer of non-superconducting material is arranged between two layers of a superconductor material in one embodiment described, the superconductor is YBa2Cu3O7-y and the non-superconductor is silver sulphate Ag2SO4. The silver sulphate being connected to the superconductor through layers of silver which serve to prevent diffusion of the sulphate into the superconductor.

The existence of an electrical field-effect in copper oxide high-Tc superconductors (although later found to be very small) has already been reported by H. Kahawata et al. in Japanese Journ. of Appl. Phys. 29 L86, 1990, and EP-A-0 324 044 actually describes a three-terminal field-effect device with a superconducting channel. Electrical fields are used to control the transport properties of channel layers consisting of high-Tc superconductor material. While this seemed to be a promising approach, growth studies of such devices have shown that in the suggested configuration, the ultrathin superconducting layers readily degrade during deposition of insulator layer and top electrode.

The lattice constant matching problem has been tackled by using doped and undoped versions of the same material. In particular, the substrate, is used as the gate electrode of a field-effect transistor of the MISFET type. The substrate consists of conducting niobium-doped strontium titanate. On top of that substrate, a barrier layer consisting of undoped strontium titanate is epitaxially grown, and onto the latter the current channel layer consisting of the superconducting YBa2Cu3O7-y, is epitaxially deposited. It has been found (cf. H. Hagesawa et al., Jap. Journ. Appl. Phys., Vol. 28 (1989) L921) that during film growth a thin insulating surface layer forms on the Nb-doped SrTiO3, reducing the sensitivity of the device. The formation of this layer is possible due to a diffusion of Nb atoms from the gate/insulator interface into the bulk of the gate electrode.

SUMMARY OF THE INVENTION

It is an object of the present invention to overcome these disadvantages of the prior art. In accordance with the invention, metallic strontium ruthenate (or strontium ruthenium oxide) Sr2RuO4 is used as substrate material for the high-Tc superconductor and circuit elements formed from the high-Tc superconductor. These superconducting circuit elements, namely SNS heterostructures, such as e.g. Josephson junctions and field-effect transistors, have a sandwich structure consisting of at least one layer of high-Tc superconductor material arranged adjacent to a metallic substrate, possibly with an insulating layer in between, the substrate, the superconductor and if-present the insulator all consisting of materials having at least approximately matching molecular structures and lattice constants.

Electrical contacts, such as source, drain and gate electrodes are attached to the superconductor layer and to the substrate, respectively. The electrically conductive substrate consists of a metallic oxide such as strontium ruthenate Sr2RuO4, whereas the superconductor layer is of the copper oxide type and may be YBa2Cu3O7-y, for example. The insulator layer may consist of SrTiO3.

The manufacture of these devices starts with the preparation of the substrate material from a 2:1:1 molar ratio of SrCO3 to RuO2 and involves a floating zone melting process yielding single crystals of the strontium ruthenate Sr2RuO4 material onto whose (001) surface the superconductor layer as well as the barrier layer can be epitaxially deposited.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 shows the resistivity p-versus-temperature characteristic of Sr2RuO4.

FIG. 2 is a diagram showing the resistance of a YBa2Cu3O7-δ film grown on a Sr2RuO4 substrate in dependence on temperature;

FIG. 3 shows an SNS heterostructure with a Sr2RuO4 substrate;

FIG. 4 is an inverted MISFET structure using a Sr2RuO4 substrate;

FIG. 5 shows essentially the device of FIG. 4 with a supporting layer.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The prior art problem of undesired surface layers on the Nb-doped SrTiO3 can be avoided if substrates are used as gate electrodes which are intrinsically metallic and that do not rely on dopants to induce metallic behavior. However, the intrinsically metallic substrate must be compatible with the high-Tc superconductor material.

Most of the high-Tc superconductor materials known today have very similar molecular structures and essentially the same lattice constants. Examples of high-Tc superconductors of the copper oxide type which can be used in connection with the present invention are listed in the table below, together with the respective reference where a description can be found:

<table>
<thead>
<tr>
<th>Superconductor Composition</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Ti-Ba-Ca-Cu-O</td>
<td>EP-A-0 332 309</td>
</tr>
</tbody>
</table>
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5,310,706

-continued

Superconductor Composition | Reference
---|---
Ti-Ba-Ca-Y-CuO | EP-A-0 368 210
Bi-Sr-Ca-CuO | EP-A-0 332 291
Bi-Sr-Ca-CuO | EP-A-0 362 000
Bi-Sr-CuO | EP-A-0 366 510
Bi-Pb-Sr-Ba-CuO | EP-A-0 348 896
Bi-Pb-Sr-Ca-CuO | EP-A-0 400 666
La-Y-Ba-Cr-CuO | EP-A-0 287 810
Eu-Ba-CuO | EP-A-0 310 246
Yb-Ba-CuO | EP-A-0 310 247
Sr-La-CuO | EP-A-0 301 958

In addition to the high-Tc copper oxide superconductor materials of which examples are listed above, there are some other high-Tc superconductor materials known which do not rely on copper but other elements, such as bismuth, for example. On such material in Ba2K0.4BiO3 which was described by R. J. Cava et al., "Superconductivity Near 30 K Without Copper: The Ba2K0.4BiO3 Perovskite", Nature, Vol. 332, No. 6167, pp. 814–816 (1988). The common characteristic of all known high-Tc superconductor materials which may be used in connection with the invention is that they have a perovskite or perovskite-related structure.


Without intending to be restrictive, the description of the invention given below will use YBa2Cu3O7-δ (with 0 ≤ δ ≤ 1) as an example of a high-Tc superconductor material, with the understanding that any other high-Tc superconductor material can be used instead, provided its molecular structure and lattice constants are sufficiently close to those of strontium ruthenate Sr2RuO4, and this is the case at least with all known high-Tc copper oxide superconductors and the bismuth oxide compound mentioned above.

In accordance with the present invention, the disadvantages of the prior art are overcome by superconducting circuit elements having a multilayered structure, comprising at least one layer of a high-Tc superconductor material arranged adjacent to a substrate consisting of a metallic conductor material having a molecular structure and lattice constants which at least approximately match those of said high-Tc superconductor material, the circuit elements being characterized in that said high-Tc superconductor material is of the perovskite-related type and that said electrically conductive substrate consists of strontium ruthenate Sr2RuO4.

The existence of Sr2RuO4 as a bulk material and a high paramagnetic electrical conductor, is already known from reports by J. J. Randall et al., "The Preparation of Some Ternary Oxides of the Platinum Metals", J. Am. Chem. Soc., Vol. 81 (1959) pp. 2629–2631, and by A. Callaghan et al., "Magnetic Interactions in Ternary Ruthenium Oxides", Inorganic Chem., Vol. 5, No. 9 (1966) pp. 1572–1576. Of course, at the time of these reports, the high-Tc copper oxide superconductor materials were still unknown. Single-crystals of Sr2RuO4 were grown for the first time by the inventors and revealed a highly conductive metallic in-plane behavior which had not been known from the ceramic Sr2RuO4 bulk material.

The method for manufacturing superconducting circuit elements in accordance with the invention is characterized by the following steps:

- Weighing appropriate ratios of strontium carbonate SrCO3 and ruthenium dioxide Ru2O3, and grinding;
- Mixing the powder with water and pressing it to form two rods;
- Sintering the rods in air at a temperature of about 1300° C.;
- Melting the rods in an air in a floating zone melting process;
- Growing samples from the melt having cylindrical shape with layers (a-b-planes) of strontium ruthenate Sr2RuO4 along the axis of the cylinder;
- Cleaning the melt-grown samples to obtain single-crystal substrates having defined crystallographic surfaces;
- Rinsing the substrate in a cleaning solvent;
- Attaching the single crystal to the heater of a sputtering chamber and sputtering with the following parameters:
  - substrate heater block temperature: 700°–750° C.;
  - total pressure (Ar2/O2 = 2:1): 0.845 mbar;
  - plasma discharge: 150–170 V, 150 mJ, 150 mJ;
- aftergrowth cooldown in ≈0.5 bar O2 lasting for ≈1 hour;
- Epitaxially growing on at least one (001)-surface of the Sr2RuO4 substrate a film of a high-Tc superconducting material, with the thickness of the superconductor film being in the range of 1 to 1000 nm;
- Depositing metal pads onto the superconductor layer(s) to form electrical contacts;
- Applying a metal pad to the surface of the substrate facing away from said superconducting layer to form an electrical contact.

Details of three embodiments of the invention will thereafter be described by way of example and with reference to the drawings in which:

FIG. 1 shows the resistivity ρ- versus-temperature characteristic of Sr2RuO4;

FIG. 2 is a diagram showing the resistance of a YBa2Cu3O7-δ film grown on a Sr2RuO4 substrate in dependence on temperature;

FIG. 3 shows an SNS heterostructure with a Sr2RuO4 substrate;

FIG. 4 is an inverted MISFET structure using a Sr2RuO4 substrate;

FIG. 5 shows essentially the device of FIG. 4 with a supporting layer.

A metallic substrate is highly desirable for thin film applications of high-Tc superconductor materials, such as, e.g., YBa2Cu3O7-δ, for a number of reasons:

It can be used as a gate electrode in a field-effect device.
It can be used as a shunt resistance.
It has a high thermal conductivity than SrTiO3 and, therefore, allows denser packaging of the devices.
It offers a convenient electrical contact from the superconductor to the external world or to other devices.

The problem with the metals and alloys so far considered for use in connection with high-Tc superconductor materials is simply that none of them has a lattice that matches the lattice structure of the superconductor material in question to any useful extent. Also, in some cases, diffusion across the interface between the materials tends to destroy the ability to become superconducting. Accordingly, none of these metals has found an
application together with a high-$T_c$ superconductor, except, perhaps, as a contact material.

In a contrast, the paramagnetic Sr$_2$RuO$_4$ has a layered K$_2$NiF$_4$-structure and is a metallic conductor along its layers, with an excellent lattice match to copper oxide superconductors, such as YBa$_2$Cu$_3$O$_{7-δ}$. At 300 K, Sr$_2$RuO$_4$ is tetragonal with lattice constants of $a=b=0.387$ nm, and $c=1.274$ nm, as compared to YBa$_2$Cu$_3$O$_{7-δ}$ which is orthorhombic with lattice constants of $a=0.382$ nm, $b=0.389$ nm, and $c=1.17$ nm. This small lattice mismatch of (about 1.3%) compares favorably even to that between YBa$_2$Cu$_3$O$_{6.9}$ (001) and strontium titanate SrTiO$_3$ (100), the latter being the standard insulating substrate for the growth of superconducting copper oxides, and which at 300 K is cubic, with $a=0.391$ nm (as shown in EP-A-0 324 220).

FIG. 1 shows the resistivity $ρ$-versus-temperature characteristic measured at a representative Sr$_2$RuO$_4$ crystal. No corrections for inhomogeneous current density distribution had to be made. In the a-b-plane, the resistivity ranges from $ρ_{ab}=10^{-4}$ $Ω$cm at room temperature down to $ρ_{ab}=10^{-6}$ $Ω$cm at 4.2 K demonstrating the highly conductive metallic in-plane behavior of Sr$_2$RuO$_4$. The observed resistivity along the c-axis resembles that of the layered materials TaS$_2$ and graphite. Like Sr$_2$RuO$_4$, they exhibit a metallic behavior along the layers and a resistivity maximum between room temperature and 4.2 K perpendicular to the layers.

Generally, when it is possible to grow Sr$_2$RuO$_4$ on SrTiO$_3$ and vice-versa, thin film devices become feasible where insulating, superconducting and metallic layers can be combined in any way.

To demonstrate their compatibility, thin films of YBa$_2$Cu$_3$O$_{7-δ}$ were grown onto the a-b-plane of a Sr$_2$RuO$_4$ crystal with very satisfactory results. The diagram of FIG. 2 shows the resistance of such a film in dependence on the temperature, with a critical temperature $T_c$ of 86 K.

Referring now to FIG. 3, there is shown an SNS heterostructure 1 comprising an electrically conducting Sr$_2$RuO$_4$ crystal forming a substrate 2 and carrying on both sides thin-film superconductor layers 3 and 4 consisting of YBa$_2$Cu$_3$O$_{7-δ}$. As mentioned above, the lattice constants of the substrate material match the lattice constants of the superconductor material to such an extent that epitaxial growth of the superconductor films 3, 5 onto the substrate 2 is possible without a problem. Contact terminals 5 and 6 are attached to superconductor layers 3 and 4, respectively.

FIG. 4 shows a field-effect transistor 7 having an inverted MISFET-structure. In this structure, a superconducting YBa$_2$Cu$_3$O$_{7-δ}$ film 8 of the thickness $s$ is separated from a Sr$_2$RuO$_4$ crystal substrate 9 serving as a gate electrode, by an insulating SrTiO$_3$ barrier layer 10 of the thickness $t$. Besides the thickness $s$ of the superconductor film 8, the resistivity $ρ_t$ and the breakthrough field strength $E_{BD}$ of the insulator layer 10 are crucial parameters. The required values for $E_{BD}$ and for $ρ_t$ can be simply estimated, if space charge effects are neglected: To induce a surface charge density in superconducting film 8 which corresponds to the unburdened density $n$ of mobile charge carriers (n$δ$ = $5×10^{11}$/cm$^3$), the capacitor formed by substrate 9 and superconductor film 8 has to be biased with a voltage $V$ where $q$ is the elementary charge, $ε_0$ and $ε_r$ respectively the dielectric constants of the vacuum and of the barrier layer material. Equation (1) rewritten provides the condition for the breakdown field strength $E_{BD}$:

$$E_{BD} = \frac{V}{d} = \frac{q}{ε_0 ε_r}$$

Equation (2) implies that to modulate the carrier density $n$ in high-$T_c$ superconductors substantially, the product $ε_r×E_{BD}$ has to be of the order of $10^3$ V/cm. (For comparison, SiO$_2$ has an $ε_r×E_{BD}$ product of $4×10^2$ V/cm at room temperature.)

In addition, the normal-state resistivity $ρ_l$ of the insulator has to be sufficiently high to avoid leakage currents which result in an input loss $V_G×1G$, the latter factor being the gate current. For a typical case of $1G=10^2$ A, $1Ω=10^4$ Ω, and an area of the substrate of 1 mm$^2$, the resistivity $ρ_l$ must be higher than $10^4$ Ωcm/$ε_l$ at operating temperature. In view of these requirements, insulating layers with high dielectric constants are recommended. Therefore, SrTiO$_3$ is a good material for insulating barrier layer 10 because of its good compatibility with the growth of copper oxide superconductors, such as YBa$_2$Cu$_3$O$_7$.

The dielectric constant $ε_l$ of SrTiO$_3$ being between 40 and 300 (depending on the purity of the material), the breakdown field being on the order of $10^8$ V/cm, and with an operating voltage $V_G=5V$, equation (2) suggests that a monomolecular (i.e. unit cell) layer of superconductor material would meet the requirements. Accordingly, with $s=1.2$ nm and $ε_l$=260 and a carrier density $n_32$ $3×10^{11}$ cm$^{-3}$, equation (1) yields a value of $t=20$ nm.

The manufacture of the Josephson junction heterostructure of FIG. 3 and of the inverted MISFET device in accordance with FIG. 4 preferably involves the following steps:

1. Appropriate ratios, molar ratios, for example, of strontium carbonate SrCO$_3$ and rhenium dioxide RuO$_2$ are weighed with an accuracy of better than 0.0001 g.
2. After grinding, the powder is mixed with water and pressed to form rods of, say, 5 mm diameter, one 10 mm in length, the other 100 mm in length, for example.
3. The rods are sintered on Al$_2$O$_3$ boats in air at about 1300° C.
4. Using the floating zone process, the rods are melted in air in a mirror cavity with focused infrared radiation, the short rod being used as the seed, the long rod being used as the feed material.
5. Single-crystals are grown from the melt. The melt-grown samples have cylindrical shape with layers (a-b-planes) of Sr$_2$RuO$_4$ grown along the axis of the cylinder.

The growth of the Sr$_2$RuO$_4$ crystals is complicated by the volatility of RuO$_2$ which leads to the segregation of SrO. To compensate for this segregation, an excess of RuO$_2$ must be used in the starting material. A molar ratio of 2:1:1 of SrCO$_3$ and RuO$_2$ is recommended to
minimize the amount of segregated SrO. In order to grown large crystals, the amount of molten material as well as its composition should be kept constant. This is difficult to achieve probably owing to the continuous evaporation of RuO₂ and because of the low density of the rods.

6. The crystals are then cleaved.

Because of the layered structure of Sr₂RuO₄, the melt-grown samples can be cleaved easily, and single crystals may be obtained from the interior part of the cylinder. With this technique it is possible to grown a cylindrical Sr₂RuO₄ crystal of about 5 mm diameter and 10 mm length. Having prepared the single-crystal Sr₂RuO₄ substrate, the manufacture of the heterostructure 1 of FIG. 3 involves the following additional steps:

1. The substrate 2 is rinsed in acetone and propanol and attached to the heater of the sputtering chamber with silver paint, for example.

2. On the upper (001) surface of the Sr₂RuO₄ substrate 2, a superconducting film 3 of, for example, YBa₂Cu₃O₇₋δ is epitaxially grown by hollow cathode rf-magnetron sputtering, wherein the value of δ is preferably kept equal to zero, but it can be made as large as 1. The sputter parameters used encompass a substrate heater block temperature of 700°-750° C., a total pressure (Ar/O₂=2:1) of 0.845 mbar, a plasma discharge of 150-170 V and 450 mA, and an aftergrowth cooldown in ≈0.5 bar O₂ lasting for≈1 hour. The thickness of the superconductor film 3 can finally be in the range of 1 to 30 1000 nm.

3. The same step is repeated for the lower (001) surface of the Sr₂RuO₄ substrate 2 to form superconductor layer 4.

4. Electrical contacts are then made in the form of 35 indium dots, silver paint, or metal pads, such as gold pads 5 and 6, for example, on the superconductor layers 3 and 4, respectively.

The manufacture of the MISFET-structure 7 FIG. 4 involves the following steps additional to the preparation of the Sr₂RuO₄ substrate 9:

1. A (100)-oriented SrTiO₃ barrier layer 10 is epitaxially grown by reactive rf-magnetron sputtering at 6.7 Pa in an O₂/Ar atmosphere at 650° C. (temperature of the sample holder) as an insulator on top of the 45 Sr₂RuO₄ substrate 9 and is polished down to the desired final thickness.

2. On top of the thinned barrier layer 10, a superconductor film 8 (of YBa₂Cu₃O₇₋δ, for example) with the thickness s is sputtered.

3. Gold pads 11 and 12 are provided on top of the superconductor layer 8 to form source and drain contacts, respectively.

4. On the back side of the substrate 9, a gate electrode 13 in the form of a metal layer, such as a gold layer, for example, is deposited.

5. Optionally, substrate 9 and gate electrode 13 may be arranged on an insulating support layer 14, be it for stability, as indicated in FIG. 5. Support layer 14 may again consist of SrTiO₃ and be epitaxially grown by reactive rf-magnetron sputtering. The thickness of this layer can be freely chosen.

From the measurements taken with several sample embodiments of the field-effect transistor in accordance with FIGS. 4 and 5, it has been determined that the operating gate voltage Vg should be in the range between 0.1 and 30 V, preferably 5 V, the thickness s of the superconducting film should be in the range between 1 and 30 nm, and the thickness t of the insulating layer should be in the range between 3 and 100 nm.

In accordance with the invention, MISFET-type heterostructures consisting of high-Tc superconductor/SrTiO₃/Sr₂RuO₄ multilayers may be made which allow the application of electrical fields larger than 10⁷ V/cm to the superconducting films. In these devices, electric field-effects generate changes in the channel resistance. The high-Tc superconductor films have a preferred thickness on the order of 10 nm and are operated with gate voltages well below 30 Volts. The channel resistivity changes can be attributed to equally strong changes of the carrier density in the high-Tc superconductor.

It should be noted that Sr₂RuO₄ can also be used in the form of thin films for certain applications. Those skilled in the art will understand that such films can be made with any of the conventional methods, such as electron beam evaporation, thermal evaporation, chemical vapor deposition, metalorganic vapor deposition, laser ablation, rf-magnetron sputtering, spinning-on, molecular beam epitaxy, etc., for example.

While this invention has been described with respect to plural embodiments thereof, it will be understood by those with skill in the art that changes in the above description or illustrations may be made with respect to form or detail without departing from the spirit or scope of the invention.

We claim:

1. A method for manufacturing superconducting circuit elements, comprising:

   weighing and grinding a ratio of strontium carbonate SrCO₃ and ruthenium dioxide RuO₂ to form powder;

   mixing the powder with water and pressing it to form rods;

   sintering the rods in air;

   melting the rods in a floating zone melting process to form a melt.

Growing crystal materials form the melt having cylindrical shape with layers of strontium ruthenate Sr₂RuO₄ along the axis of the cylindrical shape;

cleaving the melt-grown crystal materials of Sr₂RuO₄ to obtain single-crystal substrates having defined crystallographic surfaces;

epitaxially growing on at least one (001)-surface of the Sr₂RuO₄ substrate a film of a high-Tc copper oxide-based superconductor material, the thickness of the superconductor film being in the range of 1 to 1000 nm;

depositing metal pads onto said superconductor film to form electrical contacts; and

applying a metal pad to the surface of the substrate to form an electrical contact.

2. A method for manufacturing superconducting circuit element in accordance with claim 1, wherein said high-Tc superconductor material is YBa₂Cu₃O₇₋δ, and wherein 0≤δ≤1.

3. A method for manufacturing superconducting circuit elements in accordance with claim 1, further comprising:

   epitaxially growing a (100)-oriented SrTiO₃ barrier layer onto said Sr₂RuO₄ substrate; and

   depositing a high-Tc superconductor layer on said barrier layer.

4. A method for manufacturing superconducting circuit element in accordance with claim 3, wherein said high-Tc superconductor material is YBa₂Cu₃O₇₋δ, and wherein 0≤δ≤1.
5. A method for manufacturing superconducting circuit elements in accordance with claim 1, further comprising:
  depositing on the surface of the Sr$_2$RuO$_4$ substrate
  facing away from said barrier layer an insulating support layer consisting of SrTiO$_3$ and having a thickness in the range of 100 to 1000 nm.

6. A method for manufacturing superconducting circuit element in accordance with claim 5, wherein said high-T$_c$ superconductor material is YBa$_2$Cu$_3$O$_{7-8}$ and wherein 0 ≤ δ ≤ 1.

7. A method for manufacturing superconducting circuit elements in accordance with claim 1, wherein:
  a molar ratio of 2:1 of SrCO$_3$ to RuO$_2$ is used in forming said single crystal substrates.

8. A method for manufacturing superconducting circuit element in accordance with claim 7, wherein said high-T$_c$ superconductor material is YBa$_2$Cu$_3$O$_{7-δ}$, and wherein 0 ≤ δ ≤ 1.

9. A method for manufacturing superconducting circuit elements in accordance with claim 1, wherein:
  an excess of RuO$_2$ is used to obtain a molar ratio of 2:1:1 of SrCO$_3$ to RuO$_2$ forming said single crystal substrate.

10. A method for manufacturing superconducting circuit element in accordance with claim 9, wherein said high-T$_c$ superconductor material is YBa$_2$Cu$_3$O$_{7-δ}$, and wherein 0 ≤ δ ≤ 1.
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