[54] METHOD FOR FORMING SINGLE PHASE, SINGLE CRYSTALLINE 2122 BCSCO SUPERCONDUCTOR THIN FILMS BY LIQUID PHASE EPITAXY

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[58] Field of Search .......................... 505/1, 729, 733, 742; 427/62, 63, 443.2; 156/621, 622, 662; 423/593

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ABSTRACT
A substantially single phase, single crystalline, highly epitaxial film of Bi2CaSr2Cu2O8 superconductor which has a Tc (zero resistance) of 83 K is provided on a lattice-matched substrate with no intergrowth. This film is produced by a Liquid Phase Epitaxy method which includes the steps of forming a dilute supercooled molten solution of a single phase superconducting mixture of oxides of Bi, Ca, Sr, and Cu having an atomic ratio of about 2:1:2:2 in a nonreactive flux such as KCl, introducing the substrate, e.g., NdGaO3, into the molten solution at 850° C., cooling to the solution from 850° C. to 830° C. to grow the film and rapidly cooling the substrate to room temperature to maintain the desired single phase, single crystalline film structure.

13 Claims, 6 Drawing Sheets
OTHER PUBLICATIONS


FIG. 2

TEMPERATURE °C

T1

T2

T3

T1

T2

T3

TIME (HRS)

FIG. 3

(a) 130 °C PER HOUR
(b) 200 °C PER MINUTE (QUENCHED)

NORMALIZED RESISTANCE

0.0

0.5

1.0

1.5

0

50

100

150

TEMPERATURE (K)
FIG. 4

COMPOSITION ---- Bi₂ Ca₁.₀₅ Sr₂.₁ Cu₂.₁₉ Oₓ

BACK-SCATTERING COUNTS

CHANNEL NUMBER

0  5000
1.000 10⁴
1.500 10⁴
2.000 10⁴

200  300  400  500  600  700  800

O  Ca  Cu  Sr  Bi
FIG. 7

2-theta (degrees)
METHOD FOR FORMING SINGLE PHASE, SINGLE CRYSTALLINE 2122 BCSCO SUPERCONDUCTOR THIN FILMS BY LIQUID PHASE EPITAXY

This invention was developed pursuant to research sponsored in part by the U.S. Government under NASA Grant No. NAGW-1590, and the U.S. Government may have certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to the field of superconductor materials and methods for their manufacture. More particularly, the invention relates to the use of Liquid Phase Epitaxy (LPE) methods for growing substrate supported single phase, single crystalline films of the superconductor class based on oxides of Bi, Ca, Sr and Cu, known as BCSCO, and in particular the 80 K-phase of that material known as 2122.

2. Description of the Related Art

Since the discovery of Bi-Ca-Sr-Cu-O(BCSCO)-superconducting systems in 1988 there have been numerous reports on the thin film growth of this material. High quality epitaxial films of this superconducting material are of vital importance for a large number of applications. Various techniques such as electron beam deposition, magnetron sputtering, molecular beam epitaxy, and laser ablation have been widely used for the growth of thin films of BCSCO superconducting material. These methods are extremely costly and they have not been successful in producing single crystalline film specimens. In contrast there have been only a few reports on the growth of these films by the LPE method.

The main advantage of the LPE process over other thin film techniques, with the exception of laser ablation, is the superior stoichiometric control of the grown layers in the film. This is not possible with other methods due to the different vapor pressures of the individual elements of BCSCO at fixed substrate temperatures. Moreover, because of the non-uniform stoichiometric control with these techniques, the films have to be annealed subsequent to the growth to achieve the 80 K or 110 K phases. The post deposition annealing treatment of the films imposes a severe restriction on the choice of the substrates because of the possibility of diffusion of substrate constituents into the film.

The substrates that have been so far widely used for growing superconducting films are MgO and SrTiO3. Although these substrates have a very good structural stability at higher temperatures, they suffer from a large lattice constant mismatch with the 2122 phase of BCSCO. This drawback inhibits the formation of high quality epitaxial films. Recently, LaGaO3 and NdGaO3 have been used to grow thin films of BCSCO superconducting material using the LPE technique. Both of these substrates have smaller lattice mismatch with Bi2CaSr2Cu2O8+x (Bi2CaSr2Cu2O8+x+1), than MgO and SrTiO3. However, LaGaO3 suffers the disadvantage of structural instability at higher temperatures due to its phase transition at 875°C from orthorhombic to rhombohedral structure.

The liquid phase epitaxy method has been used to grow thin films of the 2122-BCSCO phase from Bi2CaSr2Cu2O8+x+1, MgO and SrTiO3. However, LaGaO3 suffers the disadvantage of structural instability at higher temperatures due to its phase transition at 875°C from orthorhombic to rhombohedral structure. The liquid phase epitaxy method has been used to grow thin films of the 2122-BCSCO phase from Bi2CaSr2Cu2O8+x+1, MgO and SrTiO3. However, LaGaO3 suffers the disadvantage of structural instability at higher temperatures due to its phase transition at 875°C from orthorhombic to rhombohedral structure.

4. SUMMARY OF THE INVENTION

It is a general object of the present invention to provide a method for producing single phase, single crystal highly epitaxial thin films of the 2122 BCSCO superconductor on matched lattice substrates composed of the preferred single phase, single crystal BCSCO materials. It is another object of the present invention to provide such a method that is practical to perform and scale up for industrial applications.

It is another object of this invention to provide an epitaxial thin film that is fully operable at the temperature of liquid nitrogen (77 K). It is another object of this invention to provide a superconductor device component that can be employed in infrared light-based systems.

These and other objects of the present invention that will be apparent to those skilled in the art are achieved by providing a single phase, single crystalline superconductor material of the 2122 phase of BCSCO having a Tc (onset) of 90 K and a Tc (zero resistance) of 83 K on a lattice-matched single crystal substrate with no intergrowth. The 2122 phase composition of the preferred film is Bi2Ca1.05Sr1.5Cu2.14Ox and the preferred substrate is a twin free, c-axis oriented, single crystal of NdGaO3. The single phase, single crystalline superconductor film of this invention has 100% reflectivity in the infrared regions at 77 K.

The present invention also provides a method for growing substantially single phase, single crystal highly epitaxial films of the 2122 phase of BCSCO on a lattice-matched substrate without intergrowth and having excellent properties as grown without post annealing steps. This method generally comprises the steps of forming a dilute, supercooled molten solution (melt) of a single phase, superconducting mixture of the BCSCO oxides in the stoichiometric proportions for the 2122 phase (i.e., the atomic ratios of Bi:Ca:Sr:Cu are approximately 2:1:2:2) in a non-reactive flux (e.g. KCl). This melt is employed in a carefully controlled Liquid Phase
Epitaxy (LPE) process of the type generally known in the art. In this LPE process, the substrate is introduced into the melt at about 850°C and the melt is slowly cooled to about 835°C during which period the single phase, single crystalline highly epitaxial film of 2122 BCSCO is deposited on the substrate. At the end of the growth period, the film-containing substrate is rapidly cooled (i.e., quenched) to room temperature at a rate sufficient to maintain the single phase, single crystalline structure of the grown superconductor film with high Tc properties [e.g., Tc (zero resistance) = 83 K].

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic drawing in cross section of one form of apparatus useful in practicing the method of the present invention.

FIG. 2 is a graphical representation of one embodiment of the temperature/time profile for LPE growth according to the present invention.

FIG. 3 is a graphical representation of the relationship between Resistance and Temperature for two 2122 BCSCO films cooled at different rates.

FIG. 4 shows compositional analysis of a 2122 BCSCO film made according to the present invention using Rutherford Back Scattering (RBS).

FIGS. 5a and 5b show electron diffraction pattern for a NdGaO3 substrate and a 2122 BCSCO thin film respectively.

FIGS. 6a and 6b are graphical representations of the relationship between Reflectance and wavelength (in the infrared region) of 2122 BCSCO film at room temperature and 77 K respectively.

FIG. 7 is an X-ray diffraction pattern of 2122 BCSCO films cooled at different rates.

DESCRIPTION OF THE INVENTION

Three members of Bi-Ca-Sr-Cu-Oxides family have been identified to be superconductors. These members have similar crystal structures so that the metal-oxygen layers can be represented by a homologous series represented by Bi2CaSrCu2O8+,+δ. The individual superconducting phases in this family differ from each other in the number of CuO2 planes and Ca layers per unit cell. The origin of superconductivity in this family as well as in 123 YBCO and Ti-based compounds is believed to be because of the presence of CuO2 planes in the unit cell. The number of these copper-oxide planes plays the decisive role in the superconducting properties of Bi-based compounds. As their number (n) increases so do the values of the superconducting transition temperature (Tc) and lattice parameter along the c-axis. For example, in the 2021-phase n = 1, Tc = 10 K and c = 24 Å; in the 2122-phase n = 2, Tc = 80 K and c = 30 Å; and in the 2223-phase n = 3, Tc = 110 K and c = 37 Å. Similar results are found also for the different superconducting phases in the TiBaCaCu2O-x system. Among the three superconducting phases the 2122-phase represented by the chemical formula Bi2CaSr2Cu3O8 is the most promising phase both scientifically and technologically. The 10 K phase is scientifically attractive but of little technological importance because of the low value of its transition temperature and the 110 K phase is almost impossible to synthesize as a single phase material in its pure form. On the other hand, the 2122-phase with Tc=80 K can be synthesized as a single phase material in its purest form. Moreover, this material is environmentally very stable and unlike the 123 YBCO material it is pure and at least 99% pure. Any contaminant present should not be reactive with the melt or the substrate. The particle size of the starting materials for the charge generally can be in the range of from about 2 to 10 μm with particles in the range of 2 to 5 μm being preferred. Particle size can have some effect on the length of time necessary to complete the annealing step described below.

In order to form the charge of oxide materials necessary to produce the single phase 2122 BCSCO crystalline material a particulate source of Bi, Ca, Sr, and Cu must be provided. The starting materials suitable for this purpose generally include the oxides or oxide precursors of the four metallic elements. The preferred starting materials are Bi2O3, CaCO3, SrCO3 and CuO. It is preferred to employ the carbonate form of calcium and strontium and the oxide form of bismuth and copper. The selected starting materials should be highly pure, at least 99% and preferably at least 99.9% pure. Some contaminates present should not be reactive with the melt or the substrate.
The selection of a suitable substrate for carrying out the LPE process can be made primarily with regard to achieving a lattice match with the 2122-BCSCO phase and its non-reactivity with the melt. In general the substrate should be substantially pure, defect free, single crystalline and preferably oriented in one specific crystallographic direction. Substrates with intergrowth and diffusion tendencies should be avoided, if possible. A good match with the lattice constants of the 2122 phase is also important in achieving both epitaxy and single crystallinity in the superconducting film. Various substrate materials and their physical properties are known in the prior art. A particularly preferred class of substrate material is the rare earth gallates, such as LaGaO₃, PrGaO₃, NdGaO₃, SmGaO₃, EuGaO₃, GdGaO₃, TbGaO₃, DyGaO₃, HoGaO₃, ErGaO₃ and mixtures thereof. The most preferred substrate is NdGaO₃. The substrate may be provided in any convenient size and shape depending on the desired properties of the deposited superconductor layer. In practice substrates on the order of 1 cm²-2.5 cm² have been satisfactorily used in the LPE process.

In carrying out the LPE process a melt containing a homogeneous molten solution of the 2122-BCSCO in the flux material in first prepared and then brought to thermal equilibrium at a temperature below the melting point of the 2122 phase (i.e. supercooled). Forming the homogeneous melt can be accomplished in any number of ways that will be apparent to those skilled in the art, such as by simple mixing of the components. In the preferred process, the oxidic charge is first melted as described above and allowed to resolidify. The flux is then placed on top of the solid oxide mass and the mixture is reheated to a temperature above the melting point of the 2122 phase e.g. 920°-940° C. This temperature (T₁) is held for a period of time (e.g. 8 to 12 hrs. to achieve thermal equilibrium and chemical homogeneity. This thermal treatment or "soak" period (t₁) is followed by a cooling of the melt to the desired start of the growth temperature (T₂). Preferably the melt is held at this temperature for a second short soak period (t₂) of about 4 to 6 hours. The substrate is introduced into the melt after the second soak and slowly cooled to the final growth temperature (T₃) over a growth period (t₃). Finally the substrate is removed from the melt at T₃ and rapidly cooled to room temperature. A typical time/temperature profile for this preferred process is shown in FIG. 2.

Of critical importance in achieving the single phase, single crystalline highly epitaxial film of the present invention is the selection of a proper growth temperature range (i.e. T₂-T₃) coupled with an appropriate cool down of the substrate. It has been found that when growth is initiated at about 850° C. and concluded at about 830° C., and the substrate is rapidly cooled to room temperature, the stated objectives are achieved. If higher, lower or even broader T₂-T₃ ranges are employed the resulting film will not be single phase and single crystalline 2122 BCSCO. It will be recognized that some tolerance for selecting these temperatures can be permitted while still maintaining the stated objective. Thus "about 850° C." and "about 830° C." as used herein is intended to include and cover those temperatures ±1° C. The rate of slow cooling over time t₃ should be slow enough to achieve the desired single phase, single crystalline form. Typically this can be accomplished at a rate of from about 1° C. to 4° C. per hour with the preferred rate being 1.5° C-3° C. per...
hour. At these rates the growth period $t_3$ will run from about 5 to about 20 hours.

After the conclusion of the growth period it is critical to rapidly cool the substrate/superconductor thin layer to room temperature. This quenching step has been found to prevent the formation of subphases and preserve the single 2122 phase in single crystalline form. The rate of rapid cooling necessary to achieve this objective can be determined experimentally, but generally falls in the range of from about $200^\circ$C/min to about $800^\circ$C/min. Preferred are rates above about $200^\circ$C/min. Thus, the preferred quench times will be about 3 to 4 minute.

After the quench step the substrate can be washed with water or other nonreactive solvent for the flux to remove any residual flux material carried on the film.

The resulting product is a high quality single phase, single crystalline, highly epitaxial thin layer of 2122 BCSCO having excellent superconductor properties: $T_c$ (onset) = 90 K, $T_c$ (zero resistance) = 83 K. The composition of the superconductor was determined to be $\text{Bi}_2\text{Ca}_{1.05}\text{Sr}_{2.1}\text{Cu}_{2.19}\text{O}_{y}$ very close to stoichiometric 2122 BCSCO. Very smooth film having a large surface area can be produced by the method of this invention. Typical film thickness can vary from about 0.25 to 2 $\mu$m with thickness of about 0.5 to 1.0 micron being preferred for most applications and film surface areas of up to 1 cm$^2$ or more can be achieved using this process.

As will be appreciated by those skilled in the art, the product of this invention has significant commercial potential for use in many optical and electronic devices including IR photodetectors, IR Fabry - Perot Interferometers, Microwave Power Transmission and Josephson Junction Devices. Of particular significance is the high potential for use in many optical and electronic devices.

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Table 1 summarizes the results of these tests. The general temperature versus time profile for the LPE tests is shown in FIG. 2. FIG. 3 shows the temperature dependence of resistance of the film specimens measured by the standard 4-point probe method. It is important to note from FIG. 3 that if the specimens are cooled slowly to room temperature after the completion of the growth period the superconducting transition width is rather broad and the samples are epitaxial but not single crystalline (FIG. 3a). Only when they are rapidly quenched do they become single crystalline and exhibit a sharp transition between the normal and the superconducting states (FIG. 3b). The compositional analysis was done by Rutherford Back Scattering (RBS) method, as shown in FIG. 4. The compositional analysis of the quenched single crystalline films (from growth regime (i)) are found to be $\text{Bi}_2\text{Ca}_{1.05}\text{Sr}_{2.1}\text{Cu}_{2.19}\text{O}_y$ which is in excellent agreement with the theoretical value of $\text{Bi}_2\text{Sr}_2\text{CuO}_5$. FIG. 5a is the electron diffraction pattern of NdGaO$_3$ single crystal substrate. The highly crystalline nature of the 2122 film is shown in FIG. 5b. A further evidence of the highly epitaxial and crystalline nature of the film of the invention is inferred from the Fourier Transform Infrared (FTIR) measurements of reflectivity vs. wavelength at 300 K (FIG. 6a) and at 77 K (FIG. 6b). In the entire far infrared region ($\lambda = 2$ to 25 $\mu$m) the 2122 BCSCO film exhibits the theoretical limit of 100% reflectivity at 77 K.

X-ray powder diffraction measurements were done by using CuK$\alpha$ radiation to identify the phases of the films at different growth temperatures. For the films grown in the range of 880$^\circ$C to 860$^\circ$C x-ray diffraction analysis showed the presence of a superconducting 2021-phases of BCSCO ($T_c \approx 10$ K) and nonsuperconducting subphases of $\text{Ca}_2\text{CuO}_3$ and $\text{CaCu}_2\text{O}_3$. An additional subphase of Cu-Sr-oxide may also have formed in these films. The temperature dependence of the resistance for these films showed the typical semiconducting behavior. The films grown in the temperature range at 860$^\circ$-840$^\circ$C show the presence of 2122 as well as of the other subphases observed at the growth temperature regime of 880$^\circ$-860$^\circ$C. These films exhibit the onset of superconducting transition at 90 K, but zero resistance is not attained above 10 K.
Films grown in the temperature regimes of 880°–860° C. invariably consist of multiple phases irrespective of slow cooling or quenching although the zero resistance is reached at different temperatures for these two cases (Table 1).

The formation of multiple phases is substantially suppressed when the films are grown in the temperature range of 850°–830° C. FIG. 7 illustrates the x-ray powder diffraction patterns of the films grown between 850° and 830° C. and cooled at the rate of (a) 130° C. per hour and (b) 200° C. per hour. The peaks are identified as follows: 

<table>
<thead>
<tr>
<th>Growth</th>
<th>Rate of Cool-</th>
<th>Phases of BCSCO</th>
<th>Tc(,onset)</th>
<th>Tc(zero)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850-835</td>
<td>200</td>
<td>Cu2O3</td>
<td>82 K</td>
<td>90 K</td>
</tr>
<tr>
<td>880-860</td>
<td>130</td>
<td>Cu2O3</td>
<td>40 K</td>
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Quenched to room temperature in 1 minute

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<td>40 K</td>
<td>83 K</td>
</tr>
</tbody>
</table>

Quenched to room temperature in 1 minute

However, for the specimens cooled at the rate of 130° C. per hour zero resistance is not obtained even at 10 K. This is attributed to the formation of nonsuperconducting phases like calcium cuprate when the films are cooled slowly to room temperature. But, if the films are cooled at the rate of 200° C. per hour, zero resistance is achieved at 40 K.

The foregoing detailed description is intended to describe and illustrate the invention without acting as a limitation on its scope, the extent of which is to be determined by reference to the appended claims.

We claim:

1. A method for growing a substantially single phase, single crystalline highly epitaxial film of the 80 K Bi2CaSrCu2Oxide superconductor phase on a single crystal lattice-matched substrate with no intergrowth comprising the steps of:
   (a) forming a dilute supercooled molten solution of a single phase superconducting mixture of oxides of Bi, Ca, Sr, and Cu having an atomic ratio of about 2:1:2:2 in nonreactive flux;
   (b) introducing said substrate into said molten solution at a temperature of about 850° C.;
   (c) slowly cooling said molten solution from about 850° C. to about 830° C. to cause the growth of said single phase, single crystalline, highly epitaxial film of the 80 K Bi2CaSrCu2Oxide superconductor phase; and
   (d) rapidly cooling the film-coated substrate to a room temperature at a rate sufficient to maintain the single phase, single crystalline structure of the superconducting film.

2. The method of claim 1 wherein said superconductor phase is Bi2Ca1.05Sr1.1Cu2.1Ox+2 having Tc(,onset) of 90 K and Tc(,zero) of 83 K.

3. The method of claim 1 wherein said lattice-matched substrate is a rare earth gallate.

4. The method of claim 3 wherein said rare earth gallate is NdGaO3.

5. The method of claim 1 wherein said nonreactive flux is an alkali metal halide.

6. The method of claim 5 wherein said alkali metal halide is KCl.

7. The method of claim 1 wherein said single phase, superconducting mixture of oxides is prepared by annealing a mixture of said oxides of their precursors.

8. The method of claim 7 wherein the step of annealing is accomplished by heating a mixture of said oxides in air for a period of from about 50 to 100 hours at a temperature of from about 800° C. to about 880° C.

9. The method of claim 8 wherein said heating is at about 850° C. for about 100 hours.

10. The method of claim 1 wherein said slow cooling is carried out at a rate of from about 1° C./hr to about 4° C./hr.

11. The method of claim 10 wherein said rate of cooling is uniform over the cooling temperature range.

12. The method of claim 1 wherein said rapid cooling is carried out at a rate of from about 160° C./min to about 800° C./min.

13. The method of claim 12 wherein said rate of cooling is at least about 200° C./minute.