

TITLEPROCESS FOR DEPOSITING HIGH TEMPERATURE
SUPERCONDUCTING OXIDE THIN FILMS5 BACKGROUND OF THE INVENTIONField of the Invention

This invention relates to a process for producing thin films of high temperature superconducting oxides and other materials requiring high growth temperatures.

10 References

The discovery of superconductivity at temperatures above 77 K, the boiling point of liquid nitrogen, in oxides such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ has stimulated a great deal of work over the past four years. Examples of other high temperature superconducting copper oxides which have been discovered during this period are the various Bi-based copper oxides, the various Tl-based copper oxides, the mixed Bi-Tl-based copper oxides and these superconducting oxides substituted with Pb and other

20 substituents.

Much of the work relating to the use of these high temperature superconductors (HTSC) in microelectronic applications has been focused on the growth of high quality thin films. At microwave frequencies, 1-100 GHz, high quality superconducting thin films can have significantly lower values of surface resistance than copper or gold films. This low surface resistance is important for making high-performance thin film microwave circuits such as filters, resonators, and

30 delay lines.

HTSC thin-films have been prepared by a number of deposition methods including evaporation, sputtering, laser ablation, and metallo-organic chemical vapor deposition (MOCVD), see, for example, R.W. Simon, Solid

35 State Technology, p. 141, September, 1989 and J.

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Talvacchio et al., SPIE Proceedings Vol. 1292, published by SPIE Bellingham, WA, (1990). In all of the thin film deposition processes for HTSC oxide materials, the substrate temperature is a critical parameter in determining the film quality. When the temperature of the substrate onto which the thin film of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ is being deposited is low, i.e., less than about 400°C , the resulting film is amorphous and insulating. A high-temperature post-deposition anneal at $800-900^\circ\text{C}$ in oxygen is required to convert the amorphous precursor film into a superconducting film with the correct crystal structure. This two-step process is referred to as a "post-anneal" process. However, under proper deposition conditions when a thin-film of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ is deposited on a hot substrate, i.e., one at a temperature of about $550-750^\circ\text{C}$, the resulting thin-film is crystalline and superconducting directly as deposited. This process is referred to as an "in-situ" process. Films produced by an in-situ process have less surface roughness and generally superior properties when compared to films from a post anneal process. The in-situ deposition process has the added advantage of lower processing temperature requirements which makes the process compatible with a wider variety of substrate materials. In-situ processes based on laser ablation and sputtering have been found to produce high quality thin films of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ on various substrates.

All in-situ processes require a method of heating substrates uniformly and reproducibly to the required deposition temperature. At the present time, the best methods for $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{O}_{7-x}$ thin films involve direct thermal and mechanical anchoring of the substrates to a heated block as discussed in R. W. Simon, SPIE Proceedings Vol. 1187, p 2, edited by T. Venkatesan, published by SPIE Bellingham, WA, (1989). The heated

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block must be made of a material that is compatible with an oxygen atmosphere and has good thermal conductivity such as nickel. Simple mechanical clamping of the substrates to the block has proven to be unreliable and is not useful for large area substrates because of substrate breakage. Good thermal contact between the substrate and the block is usually provided by a compound with high thermal conductivity such as silver paste. However, this introduces the complication of removing the paste from the back of the substrate usually by polishing or etching. In addition, the direct thermal contact method is not compatible with the deposition of an in-situ film on both sides of the substrate. The thermal contacting compound can interact with the film on the back surface of the substrate and the compound is difficult to remove without damaging the film underneath.

The ability to deposit high quality superconducting thin films on both sides of a substrate is important for certain microwave circuit applications in order to improve performance and reliability. The film on one side of the substrate would serve as the ground plane while the film on the other side would be patterned into a microwave circuit. This invention provides a non-contact method of heating substrates to elevated temperatures for the purpose of depositing crystalline thin films of compounds, particularly films of high temperature superconducting oxides, requiring elevated growth temperatures on one or both sides of the substrate.

SUMMARY OF THE INVENTION

This invention provides an improved in-situ process for depositing on a substrate a crystalline thin film of a compound requiring an elevated growth temperature, i.e., a growth temperature of about 100°C to about

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900°C. The process is especially useful for depositing a compound requiring a growth temperature of about 500°C to about 900°C and therefore is especially useful for depositing a film of an oxide, e.g., a high temperature superconducting oxide. The improvement comprises exposing the back surface of the substrate, i.e., the surface of the substrate opposite the surface on which the thin film is deposited, to radiation from a radiant heat source thereby heating the substrate to the desired growth temperature and maintaining the radiation (and thereby the desired growth temperature) during the deposition of the thin film. Deposition can be carried out using any method, e.g., by sputtering, laser ablation, evaporation, metallo-organic chemical vapor deposition, spray pyrolysis or any other technique.

When the substrate is transparent to the radiation of the radiant heat source, the back surface of the substrate is coated with a layer of material to absorb the radiation prior to the exposure to the radiation. This absorbing material can be the same compound as that of the thin film prepared in-situ using the process of this invention. This invention thus provides a process for preparing thin films of compounds requiring elevated growth temperatures, e.g., high temperature superconducting oxides, on opposite sides of a substrate. The two thin films can be of the same compound. Superconducting films on both sides of a planar substrate would be especially useful for certain microwave applications with one plane serving as the ground plane and the other patterned to form one or more elements of a microwave circuit. The thin film on the back surface of the substrate is deposited first and can be deposited by any method, e.g., by sputtering, laser ablation, evaporation, metallo-organic chemical vapor deposition, spray pyrolysis or any other technique. The

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film on the other surface of the substrate, i.e., the front surface of the substrate, is deposited using the in-situ method of this invention.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Figure 1 is a schematic drawing showing one way of practicing the in-situ process of the invention.

Figure 2 shows the measured superconducting transition for $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films on the front and back surfaces of a 1 inch (2.5 cm) square LaAlO_3 substrate.

10 DETAILED DESCRIPTION OF THE INVENTION

For brevity, the surface of the substrate on which the thin film is deposited by the in-situ process of the invention will be referred to herein as the "front surface" of the substrate. The opposite surface of the substrate will be referred to herein as the "back surface" of the substrate.

Many oxides are compounds which can be deposited by the method of this invention. Of particular interest are the high temperature superconducting oxides such as $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$, wherein M is Y or a rare earth metal and x is from about 0 to 0.3, the various Bi-based copper oxides, the various Tl-based copper oxides, the mixed Bi-Tl-based copper oxides and these superconducting oxides substituted with Pb and other substituents.

25 The substrate can be any substrate suitable for the growth of the particular compound. Unit cell parameters, thermal expansion and lack of reaction with the compound are considerations that must be addressed in choosing a substrate. Substrates used successfully with other processes for the deposition of a particular compound will be useful for the deposition of crystalline thin films of the same compound using the process of the invention.

35 The substrate is heated by directly exposing the back surface of the substrate to radiation from a

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radiant heat source such as a quartz halogen lamp, a hot filament of Pt or Pt/Rh or commercially-available heater rods. The radiant source must be compatible with the deposition conditions. The source and the substrate must be positioned so that the proper amount of radiation impinges upon and is absorbed by the substrate thereby raising the temperature of the substrate to a temperature at which growth of the compound will occur.

Many common substrates such as sapphire and quartz which are used for thin film growth are transparent to the radiation from a radiant heat source. Therefore, prior to heating and film growth, it is necessary to coat the back surface of a transparent substrate with a radiation absorbing layer to absorb the radiation. Any material that absorbs the radiation can be used, although it is preferred to use a material having the same emissivity as that of the thin film compound to be deposited on the front surface of the substrate.

This invention also provides, for the first time, a process for depositing crystalline thin films on two sides of a substrate with the crystalline thin films being comprised of the same or different compounds requiring elevated growth temperatures. The process comprises the following steps. A crystalline thin film of the desired compound is formed on one surface of the substrate. The thin film can be deposited by any method, e.g., by sputtering, laser ablation, evaporation, metallo-organic chemical vapor deposition, spray pyrolysis or any other technique. The surface of the substrate containing the thin film, the back surface, is exposed to radiation from a radiant heat source thereby heating the substrate to the desired growth temperature of the desired compound of the second thin film to be formed on a second surface of the substrate, the front surface, and this exposure is

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maintained during the deposition of the second thin film so that the temperature of the substrate is maintained at the desired growth temperature . This second thin film can be also be deposited by any method, e.g., by sputtering, laser ablation, evaporation, metallo-organic chemical vapor depositon, spray pyrolysis or any other technique. The two thin films can both be comprised of superconducting compounds, high temperature superconducting compounds or the same high temperature superconducting compound.

Figure 1 is a schematic drawing showing one way of practicing the in-situ process of the invention. In this embodiment, there is provision for depositing thin films on two substrates simultaneously. The two substrates 1 are placed in substrate holding openings in an enclosure 2 containing a radiant heat source 3, one for each substrate. If the substrates are transparent to the radiation from the radiant heat sources, absorbing layers will have been deposited on the back surface of each substrate before they are placed in the enclosure 2, and the substrates are placed in the holders so that the sides of the substrates with the absorbing layers are facing the radiant heat sources. Off-axis sputtering from two sputtering guns 4 is the method of deposition shown in the figure, although any deposition technique could be used. Means are provided to rotate the radiant heat source and substrate holder 2. The components shown in Figure 1 are situated in a vacuum system in order to carry out sputtering.

The in-situ growth of a thin film of the high temperature superconducting oxide $MBa_2Cu_3O_{7-x}$, wherein M is Y or a rare earth metal and x is from about 0 to 0.3, can be carried out as follows. Single crystal $LaAlO_3$ substrates are preferred and are prepared by depositing a radiant heat absorbing layer on the back surface of

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the substrate. One choice for the absorbing layer is a thin film, about 1 μm thick, of $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$. It is not essential that this absorber layer film be $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ since any material that absorbs radiant heat from radiation source without degradation would be acceptable. This choice, however, enables the production of a planar substrate with $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films on both sides. The first $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ film is deposited on the back surface of the substrate, the surface of the substrate to be directly exposed to the radiation from the radiant heat source. This film can be prepared by any technique. For example, a thin film of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ can be deposited by co-evaporation of Y, BaF_2 , and Cu in the Y:Ba:Cu atomic ratio of 1:2:3 followed by a wet O_2 anneal at 800-850°C as described by P. M. Mankiewich et al., Appl. Phys. Lett. 51, 1753 (1987). Films produced with this technique have transition temperatures, T_c 's, of 91-92 K and low microwave surface resistance, i.e., ten times lower than Cu at 80 K and 20 GHz. Two substrates, each with a thin film of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ on the back surface, are then loaded into the substrate holder as shown in Figure 1. Quartz halogen lamps are the preferred radiant heat sources when depositing films of $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ because these lamps are particularly well suited for operation in the high pressures of oxygen which are useful in growing the $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ films. The substrates are heated up to about 700° C with the quartz lamps. For deposition by sputtering, off-axis sputtering using two sputter guns is preferred, as shown in Figure 1. Each sputter gun contains a sputtering target of stoichiometric $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$.

The onset of superconductivity T_c in superconducting films can be determined by using an ac circuit to detect inductance changes in a sensing coil which is

inductively coupled to the sample. The transition from a non-superconducting state to a superconducting state is detected by slowly varying the temperature and monitoring the resonant frequency. When the sample
5 passes through the transition, a rapid change in the resonant frequency occurs and the transition temperature can be determined.

EXAMPLE OF THE INVENTION

A planar substrate with $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films
10 deposited on both sides was prepared in the following manner. A 1 inch (2.5 cm) square [100] oriented single crystal LaAlO_3 substrate 0.5 mm thick was cleaned by the following process. The substrate was flooded with trichlorotrifluoroethane and methanol and scrubbed with
15 a textured cloth. It was then spray rinsed with de-ionized water and dried with nitrogen. The substrate was next soaked in sulfuric acid for 10 minutes and then immersed in a water bath. The substrate was then rinsed with isopropanol, spray rinsed with de-ionized water and
20 blow-dried with clean filtered nitrogen.

LaAlO_3 is transparent to the radiation used to heat the substrate and it is therefore necessary to deposit an absorbing layer on the back surface of the substrate. In order to produce a substrate with $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin
25 films on both sides, the absorbing material used was $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ and it was formed as follows. The cleaned substrate was loaded into a turbomolecular pumped vacuum chamber with a base pressure of less than 8×10^{-7} mbar (8×10^{-5} Pa). Y, BaF_2 and Cu were co-evaporated onto the
30 unheated LaAlO_3 substrate at the appropriate rates to give an atomic ratio of Y:Ba:Cu of 1:2:3 in the deposited film. The total deposition rate at the substrate was about 2 Å/sec (0.2 nm/sec). Y and Cu were electron-beam evaporated from separate guns and the
35 rates were controlled with Leybold-Heraeus Inficon



Sentinel III electron impact emission sensors. BaF_2 was thermally evaporated from a covered molybdenum boat and the rate was controlled with a quartz crystal evaporation monitor. The co-evaporation was carried out in the presence of oxygen at 1×10^{-5} mbar (1×10^{-3} Pa). The total film thickness was about 4500 Å (450 nm). The substrate containing the evaporated film was then placed in a standard quartz-lined tube furnace. The furnace was heated to 850°C at a rate of about $25^\circ\text{C}/\text{min}$ and the film was in wet oxygen, formed by bubbling oxygen through de-ionized water. The temperature was maintained at 850°C for 30 minutes, and the film was then cooled in dry oxygen at a rate of about $5^\circ\text{C}/\text{min}$ to about 500°C and then furnace cooled to room temperature (about 20°C).

The LaAlO_3 substrate with the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ film on the back surface was then loaded into a cryo-pumped vacuum sputter deposition system [Leybold model L560] with a radiant heater and substrate holder configuration as schematically shown in Figure 1. The substrate was placed with the $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ film on the back surface directly exposed to the radiant heat source, a quartz halogen lamp. The internal temperature of the heater was measured with a thermocouple. The output of the internal thermocouple provides a feedback signal for a standard temperature controller which controls the power to the quartz lamps. This sputtering system is equipped with two rf magnetron sputtering guns with a 3" (7.6 cm) diameter $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ target in each gun. The guns are oriented in an "off-axis" configuration to reduce negative ion bombardment effects on the substrates. The substrate temperature was raised to about 700°C at a rate $15^\circ\text{C}/\text{min}$. and maintained at this temperature during the deposition of the film by sputtering. The cryo-pump was throttled to reduce its pumping speed, and a gas

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flow of Ar (180 sccm, i.e, 180 standard cubic centimeters/minute) and O₂ (40 sccm) was used to raise the system pressure to 200 mtorr (26.7 Pa). The rf sputter guns were operated with 100 watts of rf power going to each of the two guns. This resulted in a deposition rate of about 250 Å/hr (25 nm/hr) at the substrate. The total deposition time was about 3 hours. The rf power and gas flow was turned off. The system was then backfilled with pure O₂ at a pressure of 200 torr (2.67x10⁴ Pa), and the substrate was cooled to room temperature at a rate of 15°C/min. The substrate was then removed from the system. The product is a substrate with YBa₂Cu₃O_{7-x} thin films on both sides.

The inductively measured superconducting transition of the film produced by the in-situ method of this invention is shown in Figure 2. The value of T_c, about 90 K, as well as the narrow 1-2 K width of the superconducting transition are indicative of a very high quality film. The film on the back surface of this substrate also has a T_c of about 90 K and a very narrow superconducting transition as shown in Figure 2. The fact that the film on the back surface of the substrate was not degraded by the heating process shows that this technique can be used to produce high quality in-situ grown films on both sides of a LaAlO₃ substrate.

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CLAIMSThe Invention Being Claimed Is:

5 1. A process for depositing a crystalline thin film
of a compound requiring elevated growth temperatures
onto a surface of a substrate having a front surface and
a back surface comprising exposing the back surface of
said substrate to radiation from a radiant heat source
10 to heat said substrate to a predetermined growth
temperature, and, while maintaining said radiation,
depositing said thin film onto said front surface.

 2. The process of Claim 1 wherein said growth
15 temperature is about 100°C to about 900°C.

 3. The process of Claim 2 wherein said growth
temperature is about 500°C to about 900°C.

20 4. The process of Claim 3 wherein said compound is
an oxide.

 5. The process of Claim 3 wherein said oxide is a
high temperature superconducting oxide.

25 6. The process of Claim 5 wherein said high
temperature superconducting oxide is $MBa_2Cu_3O_{7-x}$,
wherein M is Y or a rare earth metal and x is from about
0 to 0.3.

30 7. The process of Claim 6 wherein said thin film is
deposited by sputtering.

 8. The process of Claim 1 wherein the substrate is
35 transparent to said radiation of said radiant heat

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source and said back surface of said substrate is coated with a layer of material to absorb said radiation prior to said exposure.

5 9. The process of Claim 8 wherein said growth temperature is about 100°C to about 900°C.

10 10. The process of Claim 9 wherein said growth temperature is about 500°C to about 900°C.

11. The process of Claim 10 wherein said compound is an oxide.

15 12. The process of Claim 11 wherein said oxide is a high temperature superconducting oxide.

20 13. The process of Claim 12 wherein said high temperature superconducting oxide is $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$, wherein M is Y or a rare earth metal and x is from about 0 to 0.3.

14. The process of Claim 13 wherein said thin film comprised of $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$ is deposited by sputtering.

25 15. The process of Claim 14 wherein said substrate is comprised of a single crystal of LaAlO_3 .

30 16. A process for depositing a first crystalline thin film onto a first surface of a substrate, and a second thin film onto a second surface of said substrate, said crystalline thin films being the same or different and comprised of compounds requiring elevated growth temperatures, said process comprising

35 (a) forming a crystalline thin film of a first compound on the first surface of said substrate,

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(b) exposing the first surface of said substrate containing said thin film formed in (a) to radiation from a radiant heat source thereby heating said substrate to the growth temperature of a second compound, a thin film of which is to be formed on the second surface of said substrate, and, while maintaining said radiation, depositing said second thin film of said second compound.

10 17. The process of Claim 16 wherein the substrate is planar and said thin films are deposited on opposite sides of said planar substrate.

15 18. The process of Claim 17 wherein said growth temperature is about 100°C to about 900°C.

19. The process of Claim 18 wherein said growth temperature is about 500°C to about 900°C.

20 20. The process of Claim 19 wherein said compound of said second thin film is an oxide.

21. The process of Claim 20 wherein both of said compounds are oxides.

25 22. The process of Claim 21 wherein said oxides are high temperature superconducting oxides.

30 23. The process of Claim 22 wherein said high temperature superconducting oxides are the same high temperature superconducting oxide.

24. The process of Claim 23 wherein said high temperature superconducting oxide is $\text{MBa}_2\text{Cu}_3\text{O}_{7-x}$, wherein

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M is Y or a rare earth metal and x is from about 0 to 0.3.

25. The process of Claim 24 wherein said second thin
5 film is deposited by sputtering.

26. The process of Claim 25 wherein said substrate
is comprised of a single crystal of LaAlO_3 .

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