Annual Report
to
Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665-5225

July 3, 1991 - July 2, 1992

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August

Department of Ceramics
College of Engineering
SUPERCONDUCTIVITY DEVICES: COMMERCIAL USE OF SPACE

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I. Introduction

The high Tc (>95K) superconducting ceramic materials, initially developed in 1987, are now being extensively investigated for a variety of engineering applications. These applications include such devices as conducting links, rotating and linear bearings, sensors, filters, switches, high Q cavities, magnets and motors. Some of these devices take advantage of the material's ability to lose all electrical resistance at a critical temperature (Tc) while others make use of the repulsion forces generated between the magnetic field of a permanent magnet and a superconductor which is cooled below its Tc; i.e., the Meissner effect.

A device involving the first of these effects; i.e., the loss of resistance at the onset of superconductivity, has been under development at Clemson University under the sponsorship of NASA Langley for the last three years. Known as a low thermal conductivity superconducting grounding link for the SAFIRE program, this device has undergone a full year of real time testing and has shown promise of meeting some of the design specifications.

A companion device to the grounding link in the SAFIRE application is the data link between the detectors and the preamps. In contrast to the former device which is a single conductor, the data link consists of a large number of electrically isolated leads of very small cross section which are designed to carry an electrical signal yet keep the thermal losses to a bare minimum. This application is obviously more demanding from a technical standpoint than the grounding link because the technologies involved in processing and fabricating small, multiple-leded devices is considerably more complicated. Much of the work reported in this annual work involves (1) the preparation and processing of the high temperature (105K) 2223 Bi-Sr-Ca-Cu-O phase in relatively pure form, (2) the development of suitable substrate materials for the BSCCO, (3) screen printing of both 2223 BSCCO and 123 YBCO materials on the substrates and (4) evaluation of the resulting superconducting properties.

In addition to this device, development is also being carried out on the development of solid-state electromechanical actuators which can be used in a number of applications in space such as cryopump motors, anti-vibration active structures and telescope mirror correctors. Considering any of these applications, the key to the successful development of a device is the successful development of a ceramic material which can produce maximum displacement per volt input. This is especially true of the cryocooler pump application where size, efficiency and reliability are of prime consideration. This report describes the work accomplished toward this goal in the first year; i.e., (1) a review of the present state of the art in actuator technology, (2) the fabrication and processing of high strain PBZT electrostrictive materials and (3) the testing and evaluation of these electrostrictive materials.
The report is divided into two parts with Part I dealing with the processing and screen printing of the superconducting BSCCO and 123 YBCO materials, and Part II reporting on the electromechanical actuator work.
Part I.
Annual Report

SUPERCONDUCTIVITY DEVICES:
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Screen Printed Y and Bi-Based Superconductors

to

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August, 1992
Abstract

High T\textsubscript{c} superconducting thick film were prepared by a screen printing process. Y-based (YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x}) superconducting thick films were printed on 211/Al\textsubscript{2}O\textsubscript{3}, SNT/Al\textsubscript{2}O\textsubscript{3}, and YSZ substrates. Because of poor adhesion of the superconductor thick films to 211/Al\textsubscript{2}O\textsubscript{3} and SNT/Al\textsubscript{2}O\textsubscript{3} substrates, relatively low T\textsubscript{c} and J\textsubscript{c} values were obtained from the films printed on these substrates. Critical temperatures (T\textsubscript{c}) of YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick films deposited on 211/Al\textsubscript{2}O\textsubscript{3} and SNT/Al\textsubscript{2}O\textsubscript{3} substrates were about 80 K. The critical current densities (J\textsubscript{c}) of these films were less than 2 A/cm\textsuperscript{2}. Higher T\textsubscript{c} and J\textsubscript{c} YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick films were printed on YSZ substrates. A YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick film with T\textsubscript{c}=86.4 and J\textsubscript{c}=50.4 A/cm\textsuperscript{2} was prepared by printing the film on YSZ substrate and firing at 990°C for 10 minutes. Multiple-lead samples were also prepared on the YSZ substrates. The multiple-lead samples showed lower T\textsubscript{c} and/or J\textsubscript{c} values than those of the plain samples.

The electrical properties of YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick films were determined by the microstructures of the films. The YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick films printed on the YSZ substrates, which had the best properties among the films printed on the three different kinds of substrates, had the highest density and the best particle interconnection. The YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick films with preferred orientation in (001) direction were obtained on the YSZ substrates. Cracks, which retarded the properties of the films, were found from the films deposited on the YSZ substrates. Currently, a MSZ (Magnesium Stabilized Zirconia) substrate, which had higher thermal expansion coefficient than the YSZ substrate, is used as substrate for the YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-x} thick film in order to eliminate the cracks on the film.

Bi-based superconductor thick films were printed on polycrystalline MgO and YSZ substrates. Interactions between BSCCO thick films and the YSZ substrates were observed. Various buffer layer materials were applied onto the substrates in order to avoid the interactions between the BSCCO thick films and the ZrO\textsubscript{2}-based substrates. So far, A BSCCO printed on MgO substrate with T\textsubscript{c}=89K was obtained. The J\textsubscript{c} of the film was lower than 0.1 A/cm\textsuperscript{2} by reason of poor interconnectivity of the BSCCO particles.
I. Introduction.

Among all the possible applications of high $T_c$ superconductors, electric wiring, high information density data transmission lines, magnetic shielding, and hybrid technology will probably be the first high $T_c$ components to be used. Sintering the high $T_c$ superconductor with a large volume and area is necessary for these applications. Thick film technology, which can be applied under normal atmospheric conditions, is a promising method to achieve such components. Several thick film fabrication methods have recently been proposed and demonstrated, e.g., screen printing, molten oxide process, rapid quench method, tape casting, and spray pyrolysis.

A YBa$_2$Cu$_3$O$_{7-x}$ superconductor grounding link for an infrared detector on the SAFIRE program has been successfully developed by tape casting technology at Clemson University. In this application, the superconducting link provides a low noise, low thermal conductivity connection from the sensitive atmospheric detector at 4K and pre-amplifier at 80K. This serves to conserve the helium in space and will extend the life of mission. A companion device to the grounding link, in the SAFIRE program, is the data link between the detector and the pre-amplifier. The data link involves a large number of electrically isolated leads of very small cross section which are designed to reduce the thermal losses to a bare minimum. The screen printing method as mentioned above is considered to be the most practical thick film process to fabricate the data link, because it is relatively simple, easy to pattern, and a low cost technique.

Films which were deposited by the screen printing process had numerous problems, the most serious of which was poor superconductivity. The properties of the copper oxide superconducting films were highly sensitive to the substrate materials$^{(1)}$. Random orientation of the crystallites and poor interconnectivity were considered to be the reasons for the low values of $T_c$ and $J_c$ of the films.

In this report, yittria-based and Bi-based superconducting thick films printed on various substrates are discussed according to the types of the superconductor materials used.
II. YBa$_2$Cu$_3$O$_{7-x}$ Thick Films.

II.1 Introduction.

YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films had been made on different substrates with T$_c$ between 43 and 90 K, as listed in Appendix I. Figure 1 shows the variation of T$_c$ values of the YBa$_2$Cu$_3$O$_{7-x}$ thick films on different substrates obtained from previous work\(^{(1-17)}\) by other investigators. The films printed on Al$_2$O$_3$ based substrates, which included polycrystalline alumina and sapphire, showed lower T$_c$ values and larger T$_c$ variations. The films on alumina substrates had a higher relative magnetic susceptibility change than those on YSZ (Yttrium Stabilized Zirconia), MgO, 211 (Y$_2$BaCuO$_5$), and SrTiO$_3$ substrates\(^{(1)}\). This was due to the strong reaction between Al$_2$O$_3$ and the YBa$_2$Cu$_3$O$_{7-x}$ superconductor. The films printed on MgO and SrTiO$_3$ substrates also had large T$_c$ variations. More consistent results, which had higher T$_c$ values and smaller T$_c$ value deviations, were obtained from the ZrO$_2$ based and 211 substrates. Ranking the substrates without a buffer layer, the best results from all of the reported literatures were on the ZrO$_2$ or 211 substrates, followed in order of increasing difficulty of preparation, MgO, spinel, SrTiO$_3$, Al$_2$O$_3$, and sapphire. Therefore, YSZ and 211 were used as substrate materials in this project. In order to compare the results on YSZ and 211 substrates, a new substrate made by SrCO$_3$, Nb$_2$O$_5$, and TiO$_2$ in the composition of Sr$_{0.875}$(Ti$_{0.75}$Nb$_{0.25}$)O$_3$ was used as a substrate material in the project.

Cracks were found on YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films by Stastny\(^{(1)}\). This was due to the weak-link contact of the YBa$_2$Cu$_3$O$_{7-x}$ grains and thermal expansion mismatch between the YBa$_2$Cu$_3$O$_{7-x}$ thick film and substrates\(^{(1)}\). No or poor adhesion of the films were found when the films were printed on Al$_2$O$_3$ and YSZ substrates and fired at temperature below 950°C in O$_2$ atmosphere\(^{(3,13)}\). Adhesion between the YBa$_2$Cu$_3$O$_{7-x}$ thick film and the substrate was improved by adding Ag or Ag$_2$O to the superconductor\(^{(5,11)}\). Cracking was prevented when Ag was added to the YBa$_2$Cu$_3$O$_{7-x}$ thick films, owing to the strength imparted by the Ag\(^{(18)}\). Superconducting properties and
Figure 1: Variations of $T_c$ value of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films on different substrates. The numbers in the figure indicate the references used in this report.
density of the thick films were also enhanced by the Ag or Ag$_2$O addition\(^{(5,11,14)}\). In this project the YBa$_2$Cu$_3$O$_{7-x}$ thick films with different Ag$_2$O additions were prepared.

The properties of the YBa$_2$Cu$_3$O$_{7-x}$ thick films were also determined by the microstructures of the films. Superconducting YBa$_2$Cu$_3$O$_{7-x}$ thick films printed on YSZ substrates with (001) preferred orientation had been obtained by the melting process. The formation mechanism of the preferred orientation was caused by the interface reaction and established by Tabuchi et.al.\(^{(17)}\), as shown in Appendix II. In this report, the influence of the films' microstructure to their electrical properties are also discussed.

II.2 Experimental Procedure.

Figure 2 shows the fabrication process of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films.

The YSZ, 211, and SNT substrates were prepared by tape casting. Because 211 and SNT substrates showed higher tan $\delta$ and/or poor mechanical strength, a polycrystalline alumina substrate was used to support these substrates. The 211 and SNT tapes were wet with toluene to bond them to Al$_2$O$_3$ substrates. The 211 substrate was sintered at 1150$^\circ$C for 4 hours, whereas the SNT substrate was sintered at 1270$^\circ$C for 4 hours. After sintering, both the 211 and SNT exhibited good adhesion to the alumina substrates. The YSZ substrate, with 8 wt% Y$_2$O$_3$, was sintered at 1520$^\circ$C for 5 hours.

The YBa$_2$Cu$_3$O$_{7-x}$ raw powder was prepared by an ordinary solid state reaction method. High purity Y$_2$O$_3$, BaCO$_3$, and CuO were wet mixed and then calcined at 900$^\circ$C for 5 hours. The calcined powder was annealed at 450$^\circ$C for 12 hours before it was cooled down to room temperature. This calcination process was repeated for three times. After calcining, YBa$_2$Cu$_3$O$_{7-x}$ powder was ground, and then mixed with 10 to 30 wt% Ag$_2$O. YBa$_2$Cu$_3$O$_{7-x}$ paste was prepared by mixing the powder with a liquid organic medium. Before the paste was prepared, any interactions between YBa$_2$Cu$_3$O$_{7-x}$ powder and the organic medium was
Figure 2: Fabrication process of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films.
observed by a leaching test. In the test, 4 g of the powder was mixed with 4 g of a liquid organic medium. The mediums examined were propylene glycol, terpineol, ethanol, toluene, and trichloroethylene. After three days aging, propylene glycol became blue. This might be caused from the leaching of copper ions from the YBa$_2$Cu$_3$O$_{7-x}$ powder. However, trichloroethylene, toluene, ethanol, and terpineol remained clear. Therefore, terpineol, ethanol, and toluene were used as solvents in paste preparation. The YBa$_2$Cu$_3$O$_{7-x}$ paste was prepared by mixing the powder, terpineol, ethanol, and toluene in 30:5:1:1 ratios. In order to increase adhesion of the green film, 10 wt% of binder (Metoramic Science Inc., B73305), was added to the paste.

After the substrates and YBa$_2$Cu$_3$O$_{7-x}$ paste were prepared, the films were deposited on the substrates by printing the paste through a 200 mesh stainless steel screen. Two kinds of patterns, single and multi-lead, were printed on the substrates. The single sample size was 1 cm wide and 4 cm long. The multi-lead sample had 15 lines, as shown in Figure 3. The size of each line was 20 mils width and 1500 mils length. The space between each line was 20 mils. Films were sintered at 900 to 990°C for 5 minutes to 4 hours, in oxygen atmosphere. Electroding conditions, as determined in the previous project (Contract No. NAG-1-820), were used to apply the electrodes to the thick films.

Critical temperature of the sample showing zero resistance, $T_c$, was measured by the four-point method. The $T_c$ of the single film was measured with a constant current of 1 mA. The multi-lead sample's $T_c$ was measured at 100 μA current. The $J_c$ of the films, both single and multi-lead type, were measured at 1 μV/cm level at 77K. Film thicknesses were measured by Tencor, Alpha-step 200. Microstructure of the YBa$_2$Cu$_3$O$_{7-x}$ thick film was observed by SEM (JEOL IC848). The crystal structure of the film was analyzed with a SCINTAG diffractometer.

II.3 Results and Discussions.

II.3.1 YBa$_2$Cu$_3$O$_{7-x}$ films printed on 211/Al$_2$O$_3$ and SNT/Al$_2$O$_3$ substrates.

YBa$_2$Cu$_3$O$_{7-x}$ thick films printed on 211/Al$_2$O$_3$ substrates showed poor adhesion to the substrates when they were fired at temperatures lower than
Figure 3: Multiple-lead YBa$_2$Cu$_3$O$_{7-x}$ superconductor samples (A), Sintered YSZ substrates (B), and YSZ green tapes (C).
940°C. The poor adhesion of the film printed on the 211/Al₂O₃ substrate was due to high porosity of the substrate, as shown in Figure 4. Adding Ag₂O to the YBa₂Cu₃O₇₋ₓ films improved their adhesion to the substrates. When 30 wt% Ag₂O was added to the films, the YBa₂Cu₃O₇₋ₓ superconducting thick films with good adhesion to the 211/Al₂O₃ substrates were obtained. The YBa₂Cu₃O₇₋ₓ films showed zero resistance at 80K with 1 mA measuring current, as listed in Table 1. Figure 4 shows the microstructure of the YBa₂Cu₃O₇₋ₓ thick film printed on 211/Al₂O₃ substrate and fired at 920°C for 60 minutes. The film had a small grain size and high porosity. Poor linking between the YBa₂Cu₃O₇₋ₓ particles was observed in this sample. Because of the weak links between the YBa₂Cu₃O₇₋ₓ particles, the YBa₂Cu₃O₇₋ₓ thick films printed on the 211/Al₂O₃ substrates had much lower Tc and Jc values than those of YBa₂Cu₃O₇₋ₓ pellet or tape. The YBa₂Cu₃O₇₋ₓ thick film was composed of 211 green phase after being fired at temperature higher than 940°C, as shown in Figure 5.

Table 1: The preparation conditions and properties of YBa₂Cu₃O₇₋ₓ screen printed thick films on 211/Al₂O₃ and SNT/Al₂O₃ substrates.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Sintering Temp.</th>
<th>Sintering Time</th>
<th>Tc(K)</th>
<th>Jc(A/cm²)</th>
<th>Ag(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>211/Al₂O₃</td>
<td>900°C</td>
<td>4 hours</td>
<td>-80</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>211/Al₂O₃</td>
<td>910°C</td>
<td>2 hours</td>
<td>-80</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>211/Al₂O₃</td>
<td>920°C</td>
<td>1 hours</td>
<td>80</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>211/Al₂O₃</td>
<td>920°C</td>
<td>2 hours</td>
<td>80</td>
<td>1.0</td>
<td>30</td>
</tr>
<tr>
<td>SNT/Al₂O₃</td>
<td>950°C</td>
<td>10 min.</td>
<td>80</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>SNT/Al₂O₃</td>
<td>950°C</td>
<td>20 min.</td>
<td>82.6</td>
<td>1.8</td>
<td>20</td>
</tr>
<tr>
<td>SNT/Al₂O₃</td>
<td>950°C</td>
<td>10 min.</td>
<td>80.9</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 4: Microstructures of \(Y_2\text{BaCuO}_5/\text{Al}_2\text{O}_3\) substrate (top) and \(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\) thick film with 30\% \(\text{Ag}_2\text{O}\) on \(Y_2\text{BaCuO}_5/\text{Al}_2\text{O}_3\) substrate. Bars equal to 10 \(\mu\text{m}\).
Figure 5: Formation of $Y_2BaCuO_5$ green phase on the $YBa_2Cu_3O_{7-x}$ thick film printed on the 211/Al$_2$O$_3$ substrate, the film was fired at 940°C for 60 minutes. Bar equals to 10 μm.
Films fired on the SNT/Al₂O₃ substrates had better adhesion than those fired on 211/Al₂O₃ substrates. Smaller additions of Ag₂O were necessary for films fired on SNT/Al₂O₃ substrates because of improved film adhesion to the substrates. The Tᵥ and Jᵥ values of the YBa₂Cu₃O₇₋ₓ films on SNT/Al₂O₃ substrates are listed in Table 1. These films had Tᵥ values between 80 and 82.6 K at 1 mA measuring current. The highest Jᵥ of the films on the SNT/Al₂O₃ substrates was 1.8 A/cm², which was fired at 950°C for 20 minutes.

The SNT/Al₂O₃ substrate had higher density than the 211/Al₂O₃ substrate, as shown in Figure 6. Better adhesion of the YBa₂Cu₃O₇₋ₓ films printed on SNT/Al₂O₃ substrates than those on 211/Al₂O₃ substrates was believed to be due to the decrease porosity of the substrates. The films printed on the SNT/Al₂O₃ substrates also had larger grain size and better interconnectivity between YBa₂Cu₃O₇₋ₓ particles than those of the films on 211/Al₂O₃ substrates. Improving the interconnectivity of the YBa₂Cu₃O₇₋ₓ particles of the thick films on SNT/Al₂O₃ substrates enhanced the films' superconducting properties, as listed in Table 1.

II.3.1.2 YBa₂Cu₃O₇₋ₓ thick films printed on YSZ substrates.
YSZ substrates provided the best adhesion to the YBa₂Cu₃O₇₋ₓ thick films among the three kinds of the substrates used in this project. Table 2 lists the Tᵥ and Jᵥ values of YBa₂Cu₃O₇₋ₓ thick films printed on YSZ substrates. Ten or twenty weight percent of Ag₂O was added to the films. The films with 10 wt% Ag₂O had Tᵥ values between 81.2 and 86.1 K and Jᵥ values between 2.6 and 15.2 A/cm². The Tᵥ values of the films prepared at the same conditions varied with the film thickness. Since a constant current was applied during measuring, a thicker sample had lower current density than that of a thinner sample. Higher Tᵥ values were obtained from the thicker samples which were subjected to lower current density (19). Samples had higher Jᵥ values when their film thicknesses were in the range between 18 and 30 μm. The superconducting properties, Tᵥ and Jᵥ, of the samples were enhanced by increasing the silver content. When 20 wt% of Ag₂O was added to the YBa₂Cu₃O₇₋ₓ thick film, the Tᵥ value of the film was 84.4 K or higher. A Jᵥ value of 50.4 A/cm² was obtained from a 20 wt% Ag₂O
Figure 6: Microstructure of SNT/Al₂O₃ substructure (top) and YBa₂Cu₃O₇₋ₓ superconductor thick film with 20wt% Ag₂O on SNT/Al₂O₃ substrate (bottom). Bars equal to 10μm.
sample fired at 990°C for 10 minutes. Among the films printed on 211/Al₂O₃, SNT/Al₂O₃, and YSZ substrates, the films printed on the YSZ substrates had the highest density and the best particles interconnectivity, as shown in Figure 7. They also had the best superconducting properties among those samples. The YBa₂Cu₃O₇₋ₓ thick films with 10% Ag₂O had more crack than the films with 20% Ag₂O, as shown in Figure 7 and Appendix III. Trans-grain cracks were found on the YBa₂Cu₃O₇₋ₓ thick films with 10% Ag₂O. This was due to the thermal expansion mismatching between the films and the substrates. The thermal expansion coefficient of the YSZ substrate used in this project was 8 x 10⁻⁶ K⁻¹, as shown in Appendix IV. However, the YBa₂Cu₃O₇₋ₓ superconductor had thermal expansion coefficient from 12 to 14 x 10⁻⁶ K⁻¹. Thus, the YBa₂Cu₃O₇₋ₓ thick film printed on YSZ substrate was in a tension condition and was being subjected to that force during cooling. Little or no cracking was observed on the films with 20% Ag₂O, which had larger grain sizes than that of the films with 10% Ag₂O. The large grains of the films with 20% Ag₂O was instrumental in to avoiding cracks during cooling.

The x-ray diffraction pattern of the film with 10% Ag₂O and fired at 980°C form 10 minutes, which had granular microstructure, presented random crystal orientation, as shown in Figure 8. When the films with 20% Ag₂O were fired at 990°C for more than 5 minutes or at 980°C for 40 minutes, melted microstructures were observed from those samples, as shown in Figure 9 and Appendix V. Partial preferred orientation of the crystals in the (001) direction of YBa₂Cu₃O₇₋ₓ were obtained from the films with melted microstructures, as shown in Figure 10. The films with preferred orientation had relatively higher Jₘ values than that of the films with random orientation. However, cracks were found on the films with melted microstructures. The cracks on the samples with melted microstructures caused the Jₘ of the samples to decrease. In order to eliminate the cracks on the films, higher thermal expansion substrates must be used. Currently, a MSZ (Magnesium Stabilized Zirconia), which has higher thermal expansion coefficient than the YSZ substrate, as shown in Appendix VI, is being used in this project.
Figure 7: Microstructure of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films with 10 (top) and 20wt% (bottom) Ag$_2$O on YSZ substrates. The films were fired at 980°C for 10 minutes. Bars equal to 10 μm.
Figure 8: X-ray diffraction pattern of a YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick film with 20wt% Ag$_2$O. The film was deposited on a YSZ substrate and fired at 850°C for 10 minutes.
Figure 9: Microstructure of a YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick film with 20wt% Ag$_2$O on YSZ substrate. The film was fired at 990°C for 5 minutes. Bar equals to 10 μm.
Figure 10: X-ray diffraction pattern of a YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick film with 20wt% Ag$_2$O. The film was deposited on a YSZ substrate and fired at 990°C for 5 minutes.
Table 2: The preparation conditions and properties of YBa$_2$Cu$_3$O$_{7-x}$ screen printed thick films on YSZ substrates.

<table>
<thead>
<tr>
<th>Sintering Temp.</th>
<th>Sintering Time</th>
<th>$T_c$(K)</th>
<th>$J_c$(A/cm$^2$)</th>
<th>Thickness</th>
<th>Ag(%)</th>
</tr>
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<tr>
<td>950°C</td>
<td>60 min.</td>
<td>82.4</td>
<td>2.6</td>
<td>24 μm</td>
<td>10</td>
</tr>
<tr>
<td>970°C</td>
<td>10 min.</td>
<td>83.7</td>
<td>3.3</td>
<td>30 μm</td>
<td>10</td>
</tr>
<tr>
<td>970°C</td>
<td>60 min.</td>
<td>84.0</td>
<td>15.2</td>
<td>18 μm</td>
<td>10</td>
</tr>
<tr>
<td>970°C</td>
<td>60 min.</td>
<td>84.9</td>
<td>6.1</td>
<td>29 μm</td>
<td>10</td>
</tr>
<tr>
<td>980°C</td>
<td>10 min.</td>
<td>82.4</td>
<td>4.6</td>
<td>14 μm</td>
<td>10</td>
</tr>
<tr>
<td>980°C</td>
<td>10 min.</td>
<td>84.4</td>
<td>1.8</td>
<td>54 μm</td>
<td>10</td>
</tr>
<tr>
<td>980°C</td>
<td>30 min.</td>
<td>84.9</td>
<td>11.9</td>
<td>18 μm</td>
<td>10</td>
</tr>
<tr>
<td>980°C</td>
<td>30 min.</td>
<td>81.2</td>
<td>2.7</td>
<td>13 μm</td>
<td>10</td>
</tr>
<tr>
<td>990°C</td>
<td>5 min.</td>
<td>86.1</td>
<td>8.4</td>
<td>23 μm</td>
<td>10</td>
</tr>
<tr>
<td>990°C</td>
<td>10 min.</td>
<td>85.0</td>
<td>7.72</td>
<td>21 μm</td>
<td>10</td>
</tr>
<tr>
<td>970°C</td>
<td>60 min.</td>
<td>86.3</td>
<td>7.7</td>
<td>20 μm</td>
<td>20</td>
</tr>
<tr>
<td>980°C</td>
<td>10 min.</td>
<td>84.4</td>
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<tr>
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<td>16</td>
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<td>10 min.</td>
<td>85.8</td>
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</table>

II.3.2 YBa$_2$Cu$_3$O$_{7-x}$ multiple-lead films.

Multiple-lead thick films with 10 wt% Ag$_2$O were fabricated on YSZ substrates. The films fired at 980°C for 10 minutes had a $T_c$ value of 82 K at 100 μA measuring current as shown in Figure 11. The $J_c$ of each line at 77 K was 0.9 A/cm$^2$. The $T_c$ of this sample was in the same range as the single samples fired at the same conditions. The $J_c$ of the film, however, was about five times lower than the single sample. The multiple-lead film fired at 970°C for 60 minutes was
Figure 11: $T_c$ curve of a YBa$_2$Cu$_3$O$_{7-x}$ multiple-lead sample. The resistance was measured at a 100 μA constant current.
not in a superconducting state at 77 K with a 100μA measuring current. When the measuring current decreased to 10 μA, the sample showed zero resistance at 80.2 K. This was because of the relatively low \( J_c \) values of the sample. The sample fired at 970°C for 1 hour had serious cracking, as shown in Figure 7. The cracking yielded lower \( T_c \) and \( J_c \) values than those of the former sample, although it had a more dense film than the former. Since increasing the silver addition in the YBa\(_2\)Cu\(_3\)O\(_{7-x}\) thick film was found to enhance the superconducting properties of the films, YBa\(_2\)Cu\(_3\)O\(_{7-x}\) multiple-lead samples with 20 wt% Ag\(_2\)O is presently being printed on the YSZ substrate.

**III. BSCCO Thick Films.**

**III.1 Introduction.**

Phase transformation of BSCCO superconductor from high-\( T_c \) phase (2223) to low-\( T_c \) phase (2212) makes fabrication of BSCCO thick films more complex than that of Y-based thick film. Different compositions of lead doped BSCCO powders have been used in thick film processes, as listed in Appendix VII. Because long heat treatment time is necessary to obtain pure 2223 phase thick films and interactions occur between the BSCCO material and the substrate, a pure 2223 phase BSCCO powder is preferred to be used as a raw material to make a paste in the screen printing process. An undesirable insulating material (yellow-green in color) was found in the films fired on sapphire and YSZ substrate\(^{(17)}\). So far, the highest \( T_c \) value of the BSCCO thick films on YSZ substrates published was 72K\(^{(17)}\). Both single crystal and polycrystalline MgO substrates were noted to be the best substrate materials for BSCCO thick films\(^{(17,20,21,23)}\).

However, the MgO substrate has much higher thermal conductivity than the stabilized ZrO\(_2\) substrate\(^{(26)}\). Since the high thermal conductivity of the substrate will increase the evaporation rate of the liquid helium in the SAFIRE program, the ZrO\(_2\) based material is considered to be the best substrate material for the program.

In this research, the MgO and the ZrO\(_2\) based substrates were used.
The MgO substrate was used to investigate the best heat treatment conditions of the BSCCO thick films. In order to avoid the interaction between the BSCCO thick film and the ZrO$_2$-based substrate, various buffer layer materials were applied to the stabilized ZrO$_2$ substrate.

**III.2 Experimental Procedure.**

Two kinds of BSCCO powders of 2223 composition were prepared; i.e., (1) solid state reaction and (2) oxalate co-precipitation. In the solid state reaction method, Bi$_2$O$_3$, SrCO$_3$, CaCO$_3$, CuO, and PbO were mixed in distilled water and then dried at 110°C for 12 hours. The dry powder was calcined at 850°C for 30 hours, cooled to room temperature and crushed in a mortar and pestle. The powder was calcined with these conditions for four times before it was made into a paste. In the oxalate co-precipitation process, a clear precursor solution was prepared by mixing bismuth acetate, calcium acetate, strontium acetate, copper acetate, and lead subacetate in a methanol solution. Acetic acid and ammonium hydroxide were used to adjust the pH value of the solution. The precursor solution was slowly poured into a stirring oxalic acid / methanol solution, which produced a BSCCO oxalate co-precipitant. The co-precipitant was dried in a vacuum dryer for 8 hours. Dried BSCCO oxalate was calcined at 600°C for 6 hours to burn off the oxalate hydrocarbons. After the oxalate burned off, the BSCCO powder was further calcined at 830°C for 24 hour for 2 times.

A BSCCO paste was prepared by mixing BSCCO calcined powder with terpineol, ethanol, and toluene in 30:7:1:1 ratios. BSCCO thick films were printed on the MgO polycrystalline substrate by the same procedure used in the YBa$_2$Cu$_3$O$_{7-x}$ thick film process. Screen printed BSCCO thick films were fired at temperatures between 830 to 855°C for different times.

**III.3 Results and Discussion.**

**III.3.1 Powder Characterization.**

BSCCO powders prepared by the solid state reaction and co-precipitation methods were characterized by measuring the $T_c$ curve of a sintered pellet and the X-ray diffraction patterns of powders. Figure 12 shows the $T_c$ curve of a
Figure 12: $T_c$ curve of a BSCCO superconductor sintered pellet. The pellet was prepared by solid state reaction powder.
sintered pellet prepared from the solid state reaction powder. The pellet had a $T_c$ of 103 K. Two steps were found in the $T_c$ curve between the onset and offset temperatures. Both low and high-$T_c$ phases were found in the four times calcined oxide powder, as shown in Figure 13. Only one step was found in the $T_c$ curve of the oxalate prepared pellet, as shown in Figure 14, indicating a homogeneous, single phase 2223 material. This sample had a $T_c=105.7$ K and $J_c = 141$ A/cm$^2$.

Presently, different calcination conditions for the oxalate co-precipitated powder are under investigation in order to achieve the best calcination conditions for this powder.

III.3.2 BSCCO Thick Film.

Figure 15 shows the $T_c$ curve of a BSCCO screen printed thick film prepared by four times calcined powder. The film was fired at 845°C for 1 hour. Two steps, as found in the $T_c$ curve of the four times calcined pellet, were observed from this curve. The film was not in the superconducting state at 77 K with 1 mA measuring current. When the measuring current was decreased to 0.62 mA, the film show zero resistance at 77 K. Therefore, this film had a relatively low critical current density ($J_c$). The films prepared by co-precipitated powder were printed on MgO substrates and fired at 840°C and 845°C for different times. The film fired at 845°C for 30 minutes had a $T_c$ at 86.5K at 20μA measuring current, as shown in Figure 16. When the heat treatment time was increased to 60 minutes, the $T_c$ of the film increased to 89.0K, as shown in Figure 17. Figure 18 presents the $T_c$ curve of the film heat treated at 845°C for 120 minutes, the $T_c$ of the film decreased to 85.4K. When the BSCCO thick film was fired at 840°C for 360 minutes, the film had $T_c$ at 88.0K, as given in Figure 19. The heat treatment temperature at 840°C, thus, was considered to be a critical heat treatment temperature of the BSCCO thick film. At or lower than that temperature, the BSCCO thick films had a slow reaction rate with substrate materials. This heat treatment critical temperature was also observed in the films printed on YSZ substrates. The film printed on YSZ substrate became a semiconducting layer when it was fired at 850°C for 5
Figure 13: X-ray diffraction pattern of a solid state reaction powder after four times calcined at 845°C for 30 hours.
Figure 14: $T_c$ curve of a BSCCO superconductor sintered pellet. The pellet was prepared by oxalate co-precipitated powder and sintered at 850$^\circ$C for 30 hours.
Figure 15: $T_c$ curve of a BSCCO thick film printed on a MgO substrate. The film was annealed at 845°C for 1 hour.
Figure 16: $T_c$ curve of a BSCCO thick film printed on MgO substrate, $T_c = 86.5$K.

The film was printed by co-precipitated powder and fired at $845^\circ$C for 30 minutes.
Figure 17: $T_c$ curve of a BSCCO thick film printed on MgO substrate, $T_c = 89.0$K.

The film was printed by co-precipitated powder and fired at $845^0$C for 60 minutes.
Figure 18: $T_c$ curve of a BSCCO thick film printed on MgO substrate, $T_c = 85.4$K.

The film was printed by co-precipitated powder and fired at 845$^\circ$C for 120 minutes.
Figure 19: $T_c$ curve of a BSCCO thick film printed on MgO substrate, $T_c = 88.0$K. The film was printed by co-precipitated powder and fired at $840^\circ$C for 360 minutes.
minutes, as shown in Figure 20. When the film printed on YSZ substrate was
fired at 840°C, it maintained metallic behavior before the onset temperature, as
presented in Figure 21. So far, the BSCCO thick films printed on the YSZ
substrates have not been found in the superconducting state at temperature
higher than 77K.

The resistivity of the films printed on MgO substrate at room
temperature were in the $10^{-2}$ $\Omega$/cm range, which was in the same range as the
bulk samples. The room temperature resistivity of the films printed on the YSZ
substrate, however, were in the $10^{-1}$ range or higher. This increasing resistivity
of the films at room temperature was caused by the reaction of the films and
substrates. The more serious reaction the samples had, the higher room
temperature resistivity it had. Therefore, a buffer layer on the YSZ substrate was
necessary to obtain a superconducting thick film on it. A BSCCO buffer layer was
melted on a YSZ substrate at 880°C for 10 minutes before the BSCCO thick film
was printed on it. This sample presented the same room temperature resistivity
range as the film printed on MgO substrate and had $T_c$ at 88.4K, as given in
Figure 22. Since the BSCCO buffer layer showed metallic behavior, it could not
qualify as a buffer material for the SAFIRE project. MgO buffer layers coated on
YSZ or MSZ substrates were applied by a dip coating process. Because the MgO
layers had serious cracks, as shown in Figure 23, interaction between the BSCCO
thick film and the substrate was observed, as shown in Figure 24.

The $T_c$ curves of the BSCCO thick films printed on MgO or BSCCO
coated YSZ substrates showed two steps after the onset temperature. This was
cauised by the weak link between BSCCO particles in the films, as presented in
Figure 25. In order to obtain a BSCCO thick film with higher $T_c$ value, a dense
and low interaction with substrate BSCCO thick film must be prepared.
Presently, the best processing conditions of MgO buffer layer on YSZ or MSZ
(Magnesium Stabilized Zirconia) substrates, which can prepare cracks free
microstructure, are under investigation in order to achieve a solid MgO buffer
film on the ZrO$_2$ substrate. The BSCCO thick films will be printed on the zirconia
based substrate after the coating conditions are determined.
Figure 20: $T_c$ curve of a BSCCO thick film printed on YSZ substrate. The film was printed by co-precipitated powder and fired at 850$^\circ$C for 5 minutes.
Figure 21: $T_c$ curve of a BSCCO thick film printed on YSZ substrate. The film was printed by co-precipitated powder and fired at 840°C for 240 minutes.
Figure 22: $T_c$ curve of a BSCCO thick film printed on BSCCO/YSZ substrate. The film was printed by co-precipitated powder and fired at 845$^\circ$C for 60 minutes.
Figure 23: Microstructure of MgO buffer layer after 1500°C annealing. Bar equals to 10 μm.
Figure 24: $T_c$ curve of BSCCO thick film on 10 layers MgO coated YSZ substrate.

The film was printed by co-precipitated powder and fired at 850°C for 60
Figure 25: Microstructure of BSCCO thick film on MgO substrate. The film was printed by co-precipitated powder and fired at 845°C for 120 minutes. Bar equals to 10 μm.
IV. Summary.

1. Critical temperatures ($T_c$) of YBa$_2$Cu$_3$O$_7$-$x$ superconductor thick films were influenced by the densification of the films.
2. Cracking of the YBa$_2$Cu$_3$O$_7$-$x$ superconductor thick films and adhesion of the films to the substrates were improved by adding Ag$_2$O into the film.
3. Higher Critical current density ($J_c$) YBa$_2$Cu$_3$O$_7$-$x$ superconductor thick films with preferred orientation in the (001) direction were obtained from the films with 20wt% Ag$_2$O deposited on the YSZ substrates and fired at 990°C for 5 to 10 minutes.
4. Mutiple-lead YBa$_2$Cu$_3$O$_7$-$x$ superconducting thick film with $T_c$ = 82 K was deposited on YSZ substrate. The $J_c$ of the sample, however, was relatively low in comparison to the plain samples.
5. A pure high-$T_c$ BSCCO (2223) powder was obtained via an oxalate co-precipitation process.
6. A BSCCO thick film printed on a MgO substrate and fired at 845°C for 60 minutes had $T_c$ value at 89.0K. Because of poor interconnection, the film had a relatively low $J_c$ value.
7. A buffer layer was found to be necessary to deposit the BSCCO thick films onto YSZ substrates.

Acknowledgement

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Appendix I. Literature reviews of YBCO screen printed thick films.

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<th>Substrate</th>
<th>Binder</th>
<th>Firing Cond.</th>
<th>$T_c$(K)</th>
<th>$J_c$(A/cm$^2$)</th>
<th>Film Thickness(μm)</th>
<th>Reference</th>
</tr>
</thead>
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<td>terpineol</td>
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<td>83</td>
<td>-</td>
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<td>O$_2$</td>
<td>10 min.</td>
<td>88</td>
<td>-</td>
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<td>120</td>
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<td></td>
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<td>50</td>
<td>-</td>
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<td></td>
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<td>70</td>
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<tr>
<td>96% Al$_2$O$_3$</td>
<td>-</td>
<td>980$^\circ$C</td>
<td>68</td>
<td>90*</td>
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<td></td>
<td></td>
<td>77</td>
<td>230*</td>
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<td></td>
</tr>
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<td>86</td>
<td>30*</td>
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<td>10 min. O$_2$</td>
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<td>$J_c$(A/cm$^2$)</td>
<td>Film Thickness(μm)</td>
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<td>-</td>
<td>-</td>
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<td></td>
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<td>700</td>
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<td></td>
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<td>$\text{diethylene terpineol}$</td>
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<td>87($\text{Ag}_2\text{O}$)</td>
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<td>77(pure)</td>
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<td>-</td>
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<td>Sapphire</td>
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*: $J_c$ was measured at 4.2 K.
Figure A1: Schematic drawing of preferred orientation caused by interface reaction (17). (after J. Tabuchi)
Figure A2: Microstructure of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ superconductor thick films with 10 (top) and 20wt% (bottom) $\text{Ag}_2\text{O}$ on YSZ substrates. The films were fired at 970°C for 60 minutes. Bars equal to 10 μm.
Figure A3: Microstructure of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films with 10 (top) and 20wt% (bottom) Ag$_2$O on YSZ substrates. The films were fired at 980°C for 30 minutes. Bars equal to 10 μm.
Figure A4: Thermal expansion of the YSZ substrate.
Figure A5: Microstructure of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films with 10 (top) and 20wt% (bottom) Ag$_2$O on YSZ substrates. The films were fired at 990°C for 10 minutes. Bars equal to 10 μm.
Figure A6: Microstructure of YBa$_2$Cu$_3$O$_{7-x}$ superconductor thick films with 20wt% Ag$_2$O on YSZ substrates. The films were fired at 980°C for 40 minutes. Bar equals to 10 μm.
Figure A7: Thermal expansion of 12 mole% MgO-ZrO₂ substrate.
Appendix VII. Literature reviews of BSCCO screen printed thick films.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Film Composition</th>
<th>Firing Cond.</th>
<th>$T_c$(K)</th>
<th>$J_c$(A/cm$^2$)</th>
<th>Reference</th>
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<tr>
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<td>Bi$<em>{1.6}$Pb$</em>{0.4}$Sr$<em>{1.6}$Ca$</em>{2.4}$Cu$<em>3$O$</em>{10}$</td>
<td>865°C, 5h</td>
<td>101</td>
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<td>20</td>
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*: Samples were annealed by two steps firing program.
Part II.
Annual Report

SUPERCONDUCTIVITY DEVICES: COMMERCIAL USE OF SPACE

Development of PBZT Ceramics for Electrostrictive Actuators

to

National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23665-5225

Principal Investigator:
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Supporting Investigator:
Guang Li - Clemson University

Contract No. NAG-1-1301

August, 1992
1. Introduction

In recent years much attention has been paid to ceramic materials with large electrostrictive effects. Electrostriction, which exists in all materials, exhibits many potential applications in electronic and optically controlled system as well as precision machinery. Among the materials available so far, however, few possess electrostrictive effects large enough to be of practical usefulness. The development of new materials with high electrostrictive coefficients has been a major impetus of much research in this area. The \((\text{Pb}_{1-x}\text{Ba}_x)_{1-3z/2}\text{Bi}_z (\text{Zr}_{1-y}\text{Ti}_y)\text{O}_3\) ceramic system (PBZT) appears to be a very promising candidate because the electrostrictive effects of PBZT \(27/70/30^*\) in the system are among the largest discovered today \([1]\).

A review of the present state of the technology in ceramic actuators is given in Figure 1. As seen from this figure, a variety of direct motional modes, composite structures and bending modes are employed to produce a given displacement. The maximum displacement per input volt is obtained with composite or bender structures, however, this is usually accomplished at the expense of (1) less load bearing capability, (2) greater complexity, (3) higher cost and (4) lesser reliability. It should be noted that in the simpler direct modes, both piezoelectric and electrostrictive materials are usable; however, the electrostrictors can be driven to higher fields (and hence, higher strains) because they are not limited by ferroelectric domain switching. For example, piezoelectric materials are limited to less than 25 volts/mil (10 kV/cm) due to domain switching which leads to 'walk off', but the electrostrictive materials can be used to much higher (50 - 100 volts/mil) fields.

Examples of the strain characteristics of two high strain materials: i.e., PMN:PT and PBZT, are given in Figure 2. Of these, the PBZT materials possess higher intrinsic total strain; and thus, were selected for further investigation.

In this report we will present the results of an investigation of \((\text{Pb}_{1-x}\text{Ba}_x)_{1-3z/2}\text{Bi}_z (\text{Zr}_{1-y}\text{Ti}_y)\text{O}_3\) ceramic system with \(0.25 \leq x \leq 0.43, 0.28 \leq y \leq 0.53\) and \(0 \leq z \leq 0.02\) extending from the composition \(27/70/30^*\). The preparation and sintering of samples as well as the measurement of the electrostric-

* In this report the notation commonly used to describe the compositions of PLZT ceramics is used for PBZT, where 27 represents the mole percentage of barium content in A-site of perovskite structure and 70/30 the Zr/Ti ratio in B-site.
trictive and related properties are described. We will also discuss the characteristics of the PBZT phase diagram on the basis of the results obtained. In addition, the preparation and evaluation of two PMN:PT compositions are included for comparison with the PBZT materials.

2. Sample Preparation and Sintering

The compositions of PBZT ceramics chosen to be investigated in this report are situated along two lines in BaZrO$_3$-BaTiO$_3$-PbZrO$_3$-PbTiO$_3$ phase diagram, which is depicted in Figure 3; i.e., the vertical line along which the Pb/Ba ratio is changed while the Zr/Ti is kept constant, and the horizontal line where, conversely, the Pb/Ba is constant and the Zr/Ti changed. The two lines intersect at the composition 27/70/30.

All the PBZT samples were prepared and sintered in terms of conventional mixed-oxide processing of electronic ceramics. A flowchart of the processing is given in Figure 4. Reagent grade PbO, ZrO$_2$, TiO$_2$, BaCO$_3$ and Bi$_2$O$_3$ additive were used as starting raw materials. Weighed components were first mixed for 30 minutes, and then calcined at 925 °C for two hours. The calcined powder was milled in distilled water using Al$_2$O$_3$ balls for 6 hours. Sample pellets were obtained by pressing the milled powder with distilled water into plates of about 30x30x4 mm at a pressure of 7000 psi. The samples were sintered at 1250–1280 °C for 4 hours in a closed alumina crucible with a flowing oxygen atmosphere. To avoid the loss of PbO from samples during sintering, a PbO-rich atmosphere was maintained by placing an equalmolar mixture of PbO and ZrO$_2$ in the crucible. Sintered samples were then lapped to dimensions of 10x10x0.76 mm. The opposite sides of the lapped samples were electroded with electroless nickel electrodes.

The PMN:PT samples, PMN:PT1 (0.8375PMN–0.1375PT–0.025BT) and PMN:PT2 (0.986PMN–0.0889PT–0.0125BT), were also prepared via a mixed-oxide method. Reagent grade MgCO$_3$ and Nb$_2$O$_5$ were mixed for 1 hour and calcined at 1100 °C for 15 hours to synthesize the columbite structure MgNbO$_6$. This step is believed to be helpful in order to minimize the concentration of undesirable pyrochlore phase in the final PMN:PT product [2]. The MgNbO$_6$ powder was then mixed with PbO, TiO$_2$ and BaCO$_3$ for 1 hour, and calcined at 800 °C for 4 hours to produce
PMN:PT. The remaining preparation procedures employed for PMN:PT were identical to those for PBZT except that PMN:PT samples were sintered at 1185 °C for 3 hours. The sintered PMN:PT samples were examined by an X-ray diffractometer to confirm the perovskite structure expected. An example of PMN:PT X-ray diffraction pattern is shown in Figure 5. As seen in the figure, the pyrochlore phase was constrained to less than 3 volume percent. Lapped samples were deposited with electroless nickel or sputtered copper electrodes for the evaluation of properties.

Some of PBZT and PMN:PT samples were also fabricated by hot-pressing.

3. Sample Measurements

The dielectric properties of samples were measured at 1 kHz with an LCR meter (LEADER, LCR-7450-01). The temperature dependence of dielectric constant and loss factor were obtained by placing samples in an environmental chamber (DELTA DESIGN, 1740) in which samples were first cooled down to -20 °C and then measured at a heating rate of 2–3 °C/min up to 140 °C. The measurement of relationship between polarization (P) and electric field (E) was carried out using conventional P–E hysteresis loop equipment. The submersion method in distilled water was employed to evaluate sample density.

An experimental device using an LVDT as a displacement sensor, was made to detect the change of electrostrictive strains with electric field, which is depicted in Figure 6. Electroded samples were placed in line with the movable core of the LVDT which was held in place with a light spring in compression. Sample electrodes were parallel or perpendicular to the movable core depending on the measurement of lateral or longitudinal strain. A liquid holder was employed to contain Freon into which samples were immersed so that electric shorting during the application of electric field could be avoided. An electric field was applied to the samples continuously between negative and positive maxima. The measured results were recorded on a X–Y plotter. The sensitivity of the displacement detection was limited basically by electronic and background vibration noises. The sensitivity of the device was estimated to be 0.1 μm at a signal/noise ratio of 1.
3. Results and Discussion

The important data of PBZT samples of different compositions obtained in this study are illustrated in Table 1. The values of the dielectric constant at room temperature lie in the range from 2250 to 7790 depending on the composition of the samples. The dielectric constant of the compositions along the vertical line in the phase diagram experienced a maximum as the barium content in the A-site of the perovskite structure increased across the boundary of the rhombohedral and cubic phases, which were plotted in Figure 7. As is often the case, the maximum dielectric constant signified the phase boundary, which appeared at a composition somewhere between 29/70/30 and 32/70/30. Figure 7 also shows a similar situation occurring along the horizontal line, where the maximum in dielectric constant indicates the rhombohedral and tetragonal phase border which is located near the composition 27/68/32.

The temperature dependence of dielectric constant and loss factor for a number of selected PBZT compositions was studied. These results are given in Figures 8 and 9. All the compositions shown in the figure were characterized by a diffuse phase transition (also called relaxor transition), a type of transition that occurs at a broad range of temperatures and is manifested as a corresponding broad maximum in the change of dielectric constant with temperature. The temperatures at which the dielectric constants reached the maxima were considered to be the temperatures of transition from the rhombohedral or tetragonal ferroelectric to the paraelectric phases. The transition temperature for the compositions along the vertical line decreased, as expected, with increasing barium content.

The sample densities exhibited no significant change for the compositions studied. The slight reduction in densities with increasing barium concentration could be interpreted as due to the decrease of lead content. Higher sintering temperatures were required for the compositions with less lead. Scanning electron photomicrographs of fractured surfaces, as seen in Figure 10, show that the sintered samples were well densified with few pores and possessed homogeneous grain sizes of approximately 5 µm. It was found experimentally that the samples with smaller Zr/Ti ratio were more easily sintered to maturity, which is indicated by their higher densities.

The relationships between polarization and electric field for the samples with constant Zr/Ti ratio
are demonstrated in Figure 11. A slim-loop characteristic was found for all these samples. Hysteresis became narrow with increasing barium content. At the same time $P_{10}$, the polarization at an electric field of 10 kV/cm, decreased monotonically, as shown in Table 1. Nearly linear $P$–$E$ relationships with negligible hysteresis were obtained at the compositions having barium concentrations larger than 32 mol% suggesting that the samples were in the paraelectric cubic phase region. As clearly illustrated by the $P$–$E$ curves in Figure 12, the characteristics of the samples with constant Pb/Ba ratio changed successively from diffuse phase to the rhombohedral phase and then to the tetragonal phase as the Zr/Ti ratio decreased. In all cases, the $P$–$E$ curves could be divided into two parts. At low electric field, polarization increased rapidly with electric field. After reaching a certain magnitude, which depends on composition, polarization became saturated. The temperature dependence of $P$–$E$ relationship for the composition 27/70/30 was measured. As seen in Figure 13, it looks similar to the corresponding compositional dependence. But the reoccurrence of large hysteresis shown in the figure above a certain temperature is beyond expectation and worthy of further study since it is concerned with temperature characteristics of electrostrictive properties. It will be seen in the following discussion that electric field induced strains have a close relation with polarization.

Both longitudinal and lateral electrostrictive strains were investigated. The curves of strains vs. electric field for various PBZT compositions are presented in Figures 14, 15 and 16. $S_{1,10}$ and $S_{2,10}$ (the magnitudes of longitudinal and lateral strains, respectively, at an electric field strength of 10 kV/cm), which are representative of the potential applications of electrostrictive materials, were evaluated and are listed in Table 1. As anticipated, it was found that strains were intimately related to polarization induced by electric field. Large strains generally corresponded to large polarization; strains appeared saturated at high electric field and the hysteresis of strains was also considered to be attributed to that of polarization. In addition, the strain($S$)–electric field($E$) relationship was observed to be strongly compositionally dependent. The butterfly–like $S$–$E$ curve for the composition 27/47/53 was generated from a tetragonal ferroelectric phase. For the compositions whose strain–electric field hysteresis was small, the strains were plotted against the square of the electric field, which is shown in Figure 17. As seen in the figure, the $S$ and $E^2$ approach a linear relationship in
low electric field region, which is typical of electrostrictive materials. The electrostrictive coefficients, m_{11} (longitudinal) and m_{12} (lateral), for those compositions shown in Figure 17 were calculated according to the slope of the linear curves in the figure, and are displayed in Table 1. The longitudinal electrostrictive coefficients were found to be between 2–3 times as large as the lateral. The PBZT hot-pressed sample exhibited larger saturated strains and slightly smaller hysteresis, as shown Figure 18, compared with those under normal sintering due to the smaller grain size of the former. More discussion about this will be taken up later.

For comparison, two PMN:PT compositions with large electrostrictive strains were studied. The results are given in Table 2 and Figures 19 and 20. Although the shape and magnitude of the P–E relationship for the PMN:PT samples resemble those of PBZT ceramics in the vicinity of the composition 27/70/30, the PMN:PT values of S_{2,10} are much lower than PBZT. This result clearly shows that PBZT ceramics are superior to PMN:PT in electrostrictive properties. Hot-pressing appeared to have no effect on the magnitude of electrostrictive strain but dramatically reduced dielectric constants, probably because of the smaller grain size of the hot-pressed samples. The increase of hysteresis for the hot-pressed PMN:PT2 sample is not fully understood.

The earliest systematic investigation of pure PbZrO$_3$–PbTiO$_3$–BaZrO$_3$–BaTiO$_3$ system was performed by Ikeda [3]. His work mainly focused on the phase diagram near BaTiO$_3$ with small amounts of Pb and Zr concentrations as well as on the FR (rhombohedral ferroelectric) and FT (tetragonal ferroelectric) phase boundary. The phase diagram shown in Figure 3 was extracted from Ikeda's publication. A significant difference was observed between the boundaries for both the FR–FT and FR–PC (paraelectric cubic phase) as given by Ikeda and those based on our results (the composition with a maximum dielectric constant). A reason for this difference is discovered to be due to the small amount of dopant (2 atom % Bi$_2$O$_3$) added to the pure PBZT system in our investigation. The influence of the Bi$_2$O$_3$ additive on the physical properties of several PBZT ceramics are demonstrated in Table 1, Figures 21, 22 and 23. It can be seen in Figure 21 that the additive not only shifted the Curie points to lower temperatures but also significantly enhanced dielectric constants of the pure PBZT ceramics. Besides, a small amount of the additive reduced the hysteresis
of P–E curves by modifying sample microstructures, and increased sample density. In studying electric field induced strains of PBZT ceramics near the FR and FT boundary, Hagimura et al [4] also discovered that a few percent additive of other rare earth elements could remarkably change the strain properties which were related to the phase structures. Further investigation is needed for better understanding of the significant effect of additives on the PBZT ceramic properties.

Grain size is not supposed to have any effect on the electrostrictive strains of relaxor materials because the relaxor phenomenon originates from the compositional fluctuation in 10 nm dimensional regimes. But it was found, as was mentioned previously, that smaller grain size obtained by hot-pressing could reduce strain hysteresis in the composition 26/70/30, even though the temperature dependence of dielectric constant in this composition exhibited a broad maximum characterized by relaxor materials. Based on this grain size effect and the variation of electric field induced strain properties (magnitude and hysteresis) with composition, it is believed that there exists a region in the PBZT phase diagram where rhombohedral phase and diffuse phase coexist. This region at least covers the dark shadowed area shown in Figure 3. It could be much larger. The large strains found in this compositional region could be explained as resulting from the combined consequence of electrostrictive effects and domain reorientation of the rhombohedral phase under electric field. A similar result was also discovered by J. von Cieminiski et. al. [5]. It is this region in the PBZT phase diagram that provides greatest practical high strain compositions.

4. Conclusions

The main objective of this study was to exploit the potential applications of PBZT ceramics as actuators. A compositional region was identified in the Bi₂O₃ doped PBZT phase diagram where large electrostrictive strains and small hysteresis exist simultaneously. The $S_{1,10}$ could be as high as $12.5 \times 10^{-4}$ and strain hysteresis may be small enough to be negligible depending on the composition involved. The excellent electrostrictive properties in this compositional region is considered as to be caused by the combined consequence of electrostrictive effects and ferroelectric domain wall motion. The Bi₂O₃ additive was found to play a dominant role in improving the properties of
pure PBZT ceramics. A small amount of the additive can significantly enhance the electrostrictive and dielectric properties of PBZT ceramics probably by means of improving sinterability and microstructures. In addition, large displacements for both the $F_R-F_T$ and $F_R-P_C$ phase boundaries resulting from the additive were discovered.

It was found that PBZT ceramic materials are superior to PMN:PT in many aspects if used as actuator materials. First, PBZT ceramics possess much larger intrinsic electrostrictive strains than PMN:PT. Secondly PBZT ceramics are easy to fabricate and relatively insensitive to sintering conditions whereas PMN:PT requires complicated preparation procedures and the undesirable pyrochlore phase in PMN:PT is hard to eliminate, which significantly degrades material properties. Finally much lower dielectric constant in PBZT compared with PMN:PT is also considered as another major advantage of PBZT ceramics from the viewpoint of electrical to mechanical energy conversion.

The electrostrictive properties of PBZT ceramics can be further improved after a better understanding of the system is obtained. Further investigation is thus of practical as well as theoretical significance.

5. References

Table 1. Properties of the \((\text{Pb}_{1-x}\text{Ba}_x)_{1-3z/2}\text{Bi}_z(\text{Zr}_{1-y}\text{Ti}_y)\text{O}_3\) ceramics.

\(z=0.02\)

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Hot-pressing

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Table 2. Properties of the PMN:PT ceramics.

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Hot-pressing

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<th>(S_{2,10}\ \times\ 10^4)</th>
<th>Electrostrictive Coeff.* (m_{11})</th>
<th>Electrostrictive Coeff.* (m_{12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMN:PT2</td>
<td>12750</td>
<td>3.5</td>
<td>8.25</td>
<td>16.4</td>
<td>1.35</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\* \(\times\ 10^{16}\) (\(\text{m}^2/\text{V}^2\))
<table>
<thead>
<tr>
<th>Type</th>
<th>Configuration</th>
<th>Load Cap. (lbs.)#</th>
<th>Actuator Movement w/voltage</th>
<th>Actuator Behavior (P or E)*</th>
<th>Actuator Strain (%)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic (d\textsubscript{33} mode)</td>
<td><img src="image1.png" alt="Image" /></td>
<td>800</td>
<td>Expansion</td>
<td>P</td>
<td>0.07</td>
</tr>
<tr>
<td>Monolithic (d\textsubscript{31} mode)</td>
<td><img src="image2.png" alt="Image" /></td>
<td>800</td>
<td>Contraction</td>
<td>P</td>
<td>0.03</td>
</tr>
<tr>
<td>Monolithic (s\textsubscript{11} mode)</td>
<td><img src="image3.png" alt="Image" /></td>
<td>800</td>
<td>Expansion</td>
<td>E</td>
<td>0.07 0.20</td>
</tr>
<tr>
<td>Monolithic (s\textsubscript{12} mode)</td>
<td><img src="image4.png" alt="Image" /></td>
<td>800</td>
<td>Contraction</td>
<td>E</td>
<td>0.03 0.08</td>
</tr>
<tr>
<td>Composite Structure (d\textsubscript{33} mode) (flexten.)</td>
<td><img src="image5.png" alt="Image" /></td>
<td>350</td>
<td>Contraction</td>
<td>P</td>
<td>0.54</td>
</tr>
<tr>
<td>Composite Structure (d\textsubscript{33}/d\textsubscript{31}) (moonie)</td>
<td><img src="image6.png" alt="Image" /></td>
<td>30</td>
<td>Expansion</td>
<td>P</td>
<td>0.80</td>
</tr>
<tr>
<td>Monomorph (Bender)</td>
<td><img src="image7.png" alt="Image" /></td>
<td>&lt;1</td>
<td>Expansion/Contraction</td>
<td>P</td>
<td>1.5</td>
</tr>
<tr>
<td>Bimorph (Bender)</td>
<td><img src="image8.png" alt="Image" /></td>
<td>&lt;1</td>
<td>Expansion/Contraction</td>
<td>P</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Notes: V = Voltage, D = actuator displacement
# Maximum load on a 3/4 inch diameter rod
* P = Piezoelectric, E = Electrostrictor
** Strain values at ±25 V/mil (10 kV/cm) & ±100 V/mil (40 kV/cm)

Figure 1.
ELECTROMECHANICAL STRAIN BEHAVIOR OF ELECTROSTRICITVE ACTUATORS.

Figure 2.
Figure 3. Room temperature phase diagram for the system PbZrO$_3$–PbTiO$_3$–BaZrO$_3$–BaTiO$_3$ (PBZT), where FR denotes rhombohedral phase, FT tetragonal phase and PC paraelectric phase [3].
Weighed PbO, BaCO$_3$, ZrO$_2$, TiO$_2$ and Bi$_2$O$_3$

Mix in distilled water for 30 minutes

Calcine at 925 °C for 2 hours

Mill in distilled water for 6 hours

Sinter at 1250 °C in oxygen atmosphere for 4 hours

Lap and Electrode

Figure 4. Flowchart of PBZT processing.
Figure 5. X-ray diffraction pattern of PMN:PT ceramics.
Figure 6. The LVDT device for measurement of electrostrictive strains
Figure 7. Variation of dielectric constant with PBZT composition.
Figure 8. Temperature dependence of dielectric constant and loss factor for various PBZT compositions with constant Zr/Ti ratio.
Figure 9. Temperature dependence of dielectric constant and loss factor for various PBZT compositions with constant Pb/Ba.
Figure 10. SEM photomicrographs of PBZT ceramics.
Figure 11. Relationship between polarization and electric field for the PBZT ceramics with constant Zr/Ti ratio.
Figure 12. Relationship between polarization and electric field for the PBZT ceramics with constant Pb/Ba ratio.
Figure 13. Variation of P–E relationship with temperature.
Figure 14. Variation of longitudinal strain with electric field for PBZT ceramics.
Figure 15. Variation of lateral strain with electric field for PBZT ceramics with constant Zr/Ti ratio.
Figure 16. Variation of lateral strain with electric field for PBZT ceramics with constant Pb/Ba ratio.
Figure 17. Plot of lateral strains against the square of electric field.
Figure 18. Influence of hot-pressing on the properties of PBZT ceramics.
Figure 19. Relationship between polarization and electric field for PMN:PT ceramics.

Figure 20. Variation of lateral strain with electric field for PMN:PT ceramics.
Figure 21. Influence of Bi$_2$O$_3$ additive on pure PBZT ceramics.
Figure 22. Comparison of P–E relationship of pure PBZT with Bi$_2$O$_3$–doped PBZT ceramics.
Figure 23. Comparison of S–E relationship of pure PBZT (above) with Bi$_2$O$_3$–doped PBZT ceramics.