Effect of suspension parameters towards the fabrication of BSCCO films by electrophoretic deposition

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Abstract
Superconductor Bi-Sr-Ca-Cu-O (BSCCO) thin films were fabricated on silver by electrophoretic deposition (EPD) method. By investigating the effects of solvents and I\textsubscript{2} additives on the properties of suspension prepared of BSCCO powder, the particle charging mechanism is analyzed. Studying the effect of different solvents on the structure of BSCCO powder, isopropanol is the best dispersion solvent. Through the optimization of the I\textsubscript{2} concentration, the results show that the optimal concentration of I\textsubscript{2} is 0.08 mg ml\textsuperscript{-1}. The processing parameters critically influencing the morphology of BSCCO films are identified and optimized to obtain uniform films with high packing density of BSCCO particles. After heated at 820 °C for 20 h, the smoothest surface morphology, high c-axis orientation, and highest critical temperature (T\textsubscript{c}) of 82 K are obtained from the film prepared with optimized suspension.

1. Introduction
High temperature superconducting (HTS) thin films due to special properties of zero resistance effect, Meissner effect and Joseph effect have numerous applications in fields such as current transport, energy and magnetic shields. Among HTS, the research on Bi-Sr-Ca-Cu-O (BSCCO) superconductors has received extensive attention due to its chemical stability and simplicity of fabrication process [1]. Besides, BSCCO films can be used in various applications like Josephson junction-based devices, terahertz devices, and power application because of unique properties in terms of low surface microwave impedance, anisotropy, and intrinsic Josephson junction characteristics [2, 3]. Among the three BSCCO superconducting phases, the Bi-2201 [4] has the simplest crystal structure, a low phase formation temperature and a wide phase formation temperature range. However, its lower T\textsubscript{c} limits the application. The Bi-2212 [5] has high T\textsubscript{c} (85 K), stable phase formation, strong layered structure and other characteristics, so it has become the primary material for many researchers to study BSCCO superconducting films; and the Bi-2223 [6] has a higher transition temperature (110 K), so the study of Bi-2223 film plays an important role in both current transmission and signal detection. But due to its complex structure, difficulty of preparation and the unstable structure without Pb doping, the pure Bi-2223 film will be studied in our future research.

Several methods including sputtering [7–9], pulsed laser deposition [10], molecular beam epitaxy [11, 12], metal organic deposition method [13, 14] and sol-gel method [15, 16] have been applied to the preparation of BSCCO films to grow c-axis oriented films with pure composition and high critical temperature.

Electrophoretic deposition is a process of material production in which charged particles are deposited onto electrode by an electric field [17]. Its main advantages are: (1) simple experimental equipment, suitable for industrial production; (2) mild reaction conditions, carried out at room temperature; (3) not limited by the shape of the substrate, and a uniform thin film material can be prepared on a substrate with a complex shape and...
a porous surface; (4) easy to operate, the thickness and density of the deposited layer can be precisely obtained by controlling the process conditions.

The preparation of Bi-based superconducting films by electrophoretic deposition has been reported. In the early stage, several [18–21] researches were made on the preparation of thin film by electrophoretic deposition, especially large improvements of the oxidation, sintering, and post-annealing processes of the films. In recent years, MM Rosete et al [22, 23] studied the stability of Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi-2212) suspensions by using ethanol as a solvent and adding auxiliary electrolytes such as sodium chloride (NaCl), potassium chloride (KCl) and lithium chloride (LiCl), and obtained that LiCl was the most suitable auxiliary electrolyte for Bi-2212 suspension. At the optimal LiCl concentration, the film showed the highest $T_c$, and had a c-axis orientation and good texture. However, LiCl-doping was mainly responsible for the suppression of $T_c^{ons}$ due to that doping might participate in changes of oxygen content or oxygen ordering effects [24]. A stable suspension is fundamental to prepare BSCCO film by EPD. There are two mechanisms for stabilization of suspension: one is the theory of Derjaguin, Landau, Verwey, and Overbeek (DLVO) [25], which is the result of similar charges forming overlapping double layers (EDLs) [26] around the particles, and the other is steric stabilization [27] which occurs when adsorbed layers on the particles form protection to keep the particles apart. Therefore, dispersing the BSCCO particles in the medium is an important step in forming a well-functioning film.

In this work, BSCCO thin films were prepared on Ag substrates by EPD in organic suspension. An analysis of charging mechanism of suspension and the kinetic mechanism of electrophoretic deposition will result in a full understanding of optimal process conditions for preparing BSCCO thin films. Suspension stability under various suspension parameters such as solvent and I$_2$ additives was investigated, and the effect of deposition parameters on film microstructure was explored. Moreover, the superconducting properties of BSCCO films obtained by EPD were also evaluated.

2. Materials and methods

2.1. Preparation of suspensions

BSCCO powders (supplied by Innova Superconductor Technology Co., Ltd China) used in this study were characterized by x-ray diffractometer (D/max-2500, Rigaku Corporation, Japan), Laser particle size analyzer (LS-POP, OMEC Instruments Co., Ltd, China) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) (IRIS Intrepid II XSP, Thermo Electron Corporation, USA).

To prepare a stable and conductive suspension with a concentration of 20 g L$^{-1}$, the BSCCO powder is dispersed in various organic solvents (AR, Sinopharm, China), with or without I$_2$ ($\geq$99%, Sinopharm, China) as an additive. The solution was then stirred with an electric stirring apparatus (ZNCL-T, YuHua Instrument Technology Co., Ltd China) at 300 rpm for 30 min, and then dispersed with a high-intensity ultrasonic cleaner (KQ250DE, Kunshan Ultrasonic Instrument Co., Ltd, China) at 250 W for 1 h for complete dispersion.

The sedimentation volumes were measured by taking 10 ml of the suspension and settling it in a cylinder for 24 h. Conductivity and pH of the suspension were measured by a conductivity meter (DDSJ-308F, INESA Scientific Instrument Co., Ltd, China) and pH meter (PHS-3C, INESA Scientific Instrument Co., Ltd China), respectively. The zeta potential of BSCCO suspension diluted to 10 mg L$^{-1}$ was measured by electrophoretic light scattering technique (Zetasizer ZS90, Malvern Instruments Ltd, UK). Moreover the suspension was centrifuged at 5000 rpm in a centrifuge (DT5–2, Beijing Times Beili Centrifuge Co., Ltd China) and then 10 ml of the supernatant was digested to determine the concentration of Bi, Pb, Sr, Ca, and Cu by ICP-AES, and then precipitate was characterized by x-ray diffractometer after drying.

2.2. Fabrication of BSCCO films

Schematic diagram of preparation of BSCCO films by electrophoretic deposition is shown in figure 1. The polished silver foil and a platinum mesh (3.0 cm $\times$ 3.0 cm in plane dimension, placed 2.0 cm apart) were used as the cathode and anode, respectively. Charged BSCCO particles were deposited on the cathode under constant voltage, then the deposited BSCCO films were dried in a drying oven (GFL-45, Labotery Instrument Co., Ltd China) at 85 °C and characterized by SEM (SU8010, Hitachi Ltd, Japan) for surface morphology and x-ray diffraction for film structure. The weight of electrode increased after deposition was divided by the deposition area to calculate the deposition weight (mg cm$^{-2}$).

Eventually, the films deposited on Ag were sintered at 820 °C for 20 h and then cooled to room temperature at a heating and cooling rate of 10 °C min$^{-1}$. The entire sintering process was conducted in a mixed gas environment of 8.5% oxygen and 91.5% nitrogen at a flow rate of 200 ml min$^{-1}$. The surface microstructure of the sintered film was observed by SEM, and the film structure was characterized by x-ray diffractometer. The resistance versus temperature (R-T) was measured by physical property measurement system (PPMS-9, Quantum Design, America).
3. Results and discussion

3.1. Characterization of BSCCO powder

The XRD pattern of the BSCCO powder used in the experiment is shown in figure 2(a), which indicates that the powder corresponds to the tetragonal phase of Bi-2212 with JCPDs no.46–0431, and a minor phase from Ca$_2$PbO$_4$ is detected. According to the calculation of the line broadening according to the Scherrer’s Formula, the average grain size is about 98.9 nm. It can be seen from figure 2(b) that the average particle size of the BSCCO powder is 3.5 μm, and the narrow size distribution is beneficial for obtaining uniform films by EPD. The results measured by ICP-AES show that Bi, Pb, Sr, Ca, and Cu are the main elemental components of BSCCO powder (figure 2(c)). It also confirms that the expected Bi:Pb: Sr:Ca:Cu atomic ratio is approximately equal to 2: 2: 2: 3.

3.2. Effect of the solvents on BSCCO suspensions

The preparation of BSCCO films by EPD requires the suspension to be stable and highly conductive, which mainly depends on the physical properties of the solvent and the interaction between the particles and the solvent, so the selection of a suitable solvent is the basis for the preparation of the suspension. Owing to the properties of the BSCCO powder, the elements such as Bi are easily hydrolyzed in contact with water, so the non-aqueous solvents are selected to keep the original composition and structure from being destroyed. In the non-aqueous solvent, several organic reagents with relatively large dielectric constants (see table 1) were select, which are polar solvents and have good dissociation ability. The sedimentation volumes of the suspensions obtained by different solvents were measured, and qualities of film by EPD under the same conditions ($V = 10$ V, $t = 10$ min) were observed also, and the results are shown in table 1. At the same time, the structures of BSCCO powder in different dispersed solvents after drying were characterized by x-ray diffractometer that showed in figure 3.

It is found from table 1 that the sedimentation volume of acetyl-acetone and acetone is 0.2 cm$^3$/0.2 g, which is relatively high and therefore of poor stability. Therefore, there are almost no depositions. For solvents of methanol, ethanol, isopropanol and dimethyl sulfoxide, the sedimentation volumes of corresponding suspensions were relatively small, so they can be deposited. But the repeatability is not satisfactory, probably because the suspension is not stable enough. Obviously, pure organic solvent as dispersant cannot obtain stable suspension.

It can be seen from figure 3 that for solvents of methanol, ethanol, acetone, isopropanol and dimethyl sulfoxide, the powder structures were the same as the BSCCO powder before the dispersion, indicating that these solvents had no damage to phase structure of BSCCO powder. When the solvent is acetyl-acetone, the...
original diffraction peaks in the BSCCO powder basically disappear and new diffraction peaks appear, which indicates new phase is formed. And it may be due to that the copper in BSCCO is coordinated with acetyl-acetone (log β of the complex of copper and acetyl-acetone is 14.3), destroying the structure of superconducting powder, acetyl-acetone is not used as the dispersing solvent.

Figure 2. Characteristics of the BSCCO powders: (a) an XRD pattern, (b) the particle size distribution measured by a laser particle size analyzer, and (c) composition element ratio.

Figure 3. An XRD pattern of BSCCO dispersed in different solvents.
Consequently, it is necessary to add additive to the solvents of methanol, ethanol, acetone, isopropanol, and dimethyl sulfoxide to increase the stability of the suspension so as to obtain dense BSCCO films.

3.3. Effect of I$_2$ on BSCCO suspensions

In some reports [29, 30], it is possible that adding a small amount of I$_2$ to the alcohol or ketone to increase the protons in the solution, thereby enhancing the charging of the particles, and promoting the stability and conductivity of the oxide suspension. Similarly, I$_2$ was added to increase the stability of the BSCCO suspension in this work.

The conductivity of the suspension with and without BSCCO at different I$_2$ concentrations was measured, and the results are shown in figure 4. It can be seen that on all the curves, the conductivity increases with the increase of the I$_2$ concentration. This is because I$_2$ with empty $\sigma^*$ orbital, which can accept electrons and involve interaction between molecular orbital with donor molecular such as hydroxyl in ethanol with non-bonded electron pairs, to form a charge-transfer complex [31]. Therefore, the H$^+$ of the hydroxyl radical is dissociated in the intro-molecular oxidation-reduction process, and the H$^+$ in the solution increases, so the conductivity of the solution increases.

Without the addition of I$_2$ (as shown by the red mark in the figure 4), the suspension conductivity of isopropanol, acetone, dimethyl sulfoxide and ethanol is lower than that of pure solvent, which indicates that H$^+$ has been adsorbed on the surface of BSCCO particles. It is due to that a small amount of H$^+$ dissociated from the organic solvent is adsorbed on the BSCCO particles, and the particles mobility is lower than a single proton in the solution, resulting in a decrease of conductivity. But in the methanol solvent, the conductivity of the suspension is greater than that of the pure solvent. The reason may be that Bi, Pb, Sr, Ca, and Cu in the BSCCO

| solvent        | Dielectric constant [28] $\varepsilon_r$ | Sedimentation volumes (cm$^3$/0.2 g) | Qualities of film          |
|----------------|----------------------------------------|--------------------------------------|-----------------------------|
| Methanol       | 33.7                                   | 0.1                                  | Deposited, poor repeatability |
| Ethanol        | 24.3                                   | 0.1                                  | Deposited, poor repeatability |
| Isopropanol    | 18.3                                   | 0.1                                  | Deposited, poor repeatability |
| Dimethyl sulfoxide | 48.9                                | 0.1                                  | Deposited, poor repeatability |
| Acetyl acetone | 23                                     | 0.2                                  | Scarcely deposited          |
| Acetone        | 20.5                                   | 0.2                                  | Few deposited               |

Consequently, it is necessary to add additive to the solvents of methanol, ethanol, acetone, isopropanol, and dimethyl sulfoxide to increase the stability of the suspension so as to obtain dense BSCCO films.
powders are dissolved in the solvent. The concentrations of each ion in the supernatant after centrifuged were determined, as shown in figure 5.

It can be seen from the figure 5 that the concentration of Ca$^{2+}$ in methanol is relatively high, which also confirms that the conductivity of the methanol suspension is greater than that of the pure solvent because more Ca$^{2+}$ in the BSCCO powders is dissolved in the solvent. It can also be seen from figure 5 that the concentrations of each ion in the supernatant of the isopropanol suspension are relatively low. And figure 4 shows that the conductivity of the suspension in the isopropanol is smaller alone than the pure solvent in the range of the $I_2$ concentration less than 0.25 mg mL$^{-1}$, which fully shows that the dissolution of BSCCO powder is the lowest when isopropanol is the dispersing solvent. Therefore, isopropanol is selected as the dispersion solvent of the BSCCO suspension.

The zeta potentials and pH values of BSCCO suspension which was prepared by isopropanol as dispersing solvent with different $I_2$ concentrations were measured, and at the same time the pH values of pure isopropanol at different $I_2$ concentrations were measured also, that was shown in figure 6.

As the $I_2$ concentration increases, the pH value of the pure isopropanol solution decreases, that is, the H$^+$ concentration in the solution increases. As mentioned above, the increase of the conductivity in the solution is due to a charge transfer complex can be formed by the $I_2$ and isopropanol to increase the H$^+$ in the solution, which also indicates that the interaction of $I_2$ and isopropanol produces H$^+$. With the addition of BSCCO powders, the pH value of the suspension increases first and then decreases slowly with almost same slope of pure isopropanol solution when the $I_2$ concentration increases above 0.08 mg mL$^{-1}$, indicating that when the $I_2$ is added, the H$^+$ ions in the suspension are largely adsorbed by BSCCO, so the pH value increases. When the adsorption of BSCCO powders reaches saturation, the free H$^+$ in the suspension increases with the increasing of $I_2$, or the pH value decreases.

The zeta potential of the suspension also increases with the rise of the $I_2$ concentration, which means that there are more H$^+$ ions adsorbed on the surface of the particles, so that greatly enhances the electrostatic repulsion between the particles. When the addition amount is above 0.08 mg mL$^{-1}$, it starts to decrease slightly, because too much H$^+$ and corresponding anion increase the ion concentration of the solution, making the electric double layer of the particles thin, which is not good for the stability of the suspension. Thus the variation tendency of zeta potential and pH value is consistent, indicating that the addition of $I_2$ can increase the dissociation of H$^+$ from hydroxyl group, so as to increase the charge on BSCCO powder and stability of suspension. After adsorption saturation, the suspension maintains stable.

In order to obtain the most stable suspension, the sedimentation volume and deposition weight ($V = 10$ V, $t = 10$ min) under different $I_2$ concentrations were determined, shown in figure 7. It can be seen that when the amount of $I_2$ increases, the sedimentation volume of the suspension decreases first and then increases gradually, that is to say, the stability of the suspension decreases first and then increases, indicating that the suspension has the best stability when the concentration of $I_2$ is 0.08 mg mL$^{-1}$. Therefore, comprehensive consideration of zeta
potential, pH value, sedimentation volume and deposition weight, the optimal concentration of I\textsubscript{2} is selected as 0.08 mg mL\textsuperscript{-1}.

The SEM morphology of the as-deposited film obtained from two suspensions of BSCCO-isopropanol (figure 8(a)) and BSCCO-isopropanol-0.08 mg mL\textsuperscript{-1} I\textsubscript{2} (figure 8(b)) demonstrated that a porous structure emerged without I\textsubscript{2} addition, while the film exhibits smooth and few holes owing to the higher suspension stability with I\textsubscript{2} addition. Compared with the two, the film with I\textsubscript{2} addition is denser, so the film prepared in BSCCO isopropanol-0.08 mg mL\textsuperscript{-1} I\textsubscript{2} had a smoother surface and fewer pores than those prepared in pure isopropanol suspension.

3.4. Effect of deposition parameter on deposition rate
According to the law of conservation of mass, Hamaker [32] proposed a classic sedimentary dynamic relationship in an ideal state. For a constant-voltage deposition, the weight (w) of charged particles deposited per
unit area of the electrode in the initial period can be expressed as:

\[ w = f \cdot c_0 \varepsilon \varepsilon_0 \gamma E \eta^{-1} L^{-1} \]  
(1)

Where \( c \) represents the concentration of the particle in the suspension, \( f \) the deposition factor, \( \varepsilon_0 \) the permittivity of vacuum, \( \varepsilon \) the relative permittivity of the solvent, \( \gamma \) the zeta potential of the particle, \( E \) the applied voltage, \( t \) the deposition time, \( \eta \) the viscosity of the solvent, \( L \) the distance between electrodes.

However, during the actual electrolysis, the deposition weight is affected by many complex factors. Therefore, to investigate the effect of deposition parameters on the morphology of the film and obtain BSCCO thin films with controllable thickness, it is necessary to study the relationship of deposition weight and electrophoretic deposition parameters. The deposition weights were measured at different deposition times, deposition voltages or suspension concentrations that shown in the figure 9.

For the relationship between deposition weight and deposition time, figure 9(a) shows that before 13 min, the deposition weight of the film has a linear relationship with the deposition time, which is consistent with formula (1). After 13 min, the growth rate of the film gradually slows down and deviates from the linear relationship control area, which cannot be explained by formula (1). This is because with the progress of electrophoretic deposition, a thin layer is formed after the BSCCO particles are discharged on the cathode, then the effective voltage decreases, resulting in a decrease in the deposition rate. When the voltage across the suspension drops to a certain value, the energy of the charged particles is not enough to overcome the energy barrier in the DLVO theory, and the particles cannot be deposited on the substrate, then the electrophoretic deposition will not proceed, and the deposition quality will remain unchanged.

Will [33] based on Hamaker’s basic formula, considering changes in electric field over time, and proposed the following model:

\[ w = -k_1 + \sqrt{k_1^2 + k_2 t} \]  
(2)

Where \( k_1, k_2 \) are the constants of the equation, and the deposition weight has a linear relationship with \( t^{1/2} \) when the value of \( t \) is relatively large, which can be simplified to the following equation:

\[ w = a \sqrt{t} + b \]  
(3)

So equation (3) is in accordance with the fitting relationship of the deposition weight and deposition time after 13 min in the figure 9(a). Thus the effect of the electric field is negligible within the first 13 min. However, when the deposition time was longer than 13 min, the BSCCO films obtained were of poor quality. It seems to be optimal to select a deposition time of 10 min, since a smooth film with high density was prepared.

For formula (1), keeping other factors constant and change the applied voltage, the deposition weight has an approximately linear relationship with the applied voltage showed in figure 9(b). As the applied voltage increases, the particles in the suspension migrate faster and the amount of particles deposited is greater. At the same time, the subsequent deposition of the outer layer has a certain force on the particles that have been accumulated in the inner layer, so that the inner layer can be more closely combined with the substrate, to make the density of the obtained film better. Figure 10 shows the SEM morphology of the as-deposited film obtained at different deposition voltages (\( c = 20 \text{ g L}^{-1}, t = 5 \text{ min} \)), from which it can be seen that the higher deposition voltage, the fewer pores on the film surface. Therefore, a higher applied voltage can provide energy for particles with a wider range of particle sizes to overcome the barrier. After the large-size particles are deposited, the small-size particles can be filled in the pores between the large particles, thereby making the overall density of film better. However, the acceleration of the deposition rate would cause the electrode surface diffusion rate to fail to

Figure 8. Morphology of the BSCCO films fabricated from various suspensions: a) BSCCO-isopropanol by EPD; b) BSCCO-isopropanol-0.08 mg mL\(^{-1}\) I\(_2\) by EPD.
keep up with the deposition rate, resulting in a decrease in the surface concentration, and the curve would bend toward the horizontal axis. If the deposition voltage is too high, the deposition speed would be too fast, and the particles would not have enough time to be arranged on the substrate in a suitable form, which would cause the film to crack, so the deposition voltage is selected as 10 V.

Figure 9. Effect of deposition conditions on deposition weight: (a) different deposition times; (b) different applied voltages; and (c) different BSCCO concentrations in the suspension.

Figure 10. Morphology of the BSCCO films fabricated at different voltages: (a) 5 V; (b) 7 V; (c) 10 V.
Figure 9(c) showed that when the suspension concentration is less than 50 g L$^{-1}$, the deposition weight increases linearly with the suspension concentration. When the suspension concentration is higher than 50 g L$^{-1}$, the rate of increase in deposition weight is relatively slow, which may be due to that high BSCCO

Figure 11. Morphology of the BSCCO films fabricated from various suspensions of different concentrations: (a) 10 g l$^{-1}$; (b) 20 g l$^{-1}$; (c) 30 g l$^{-1}$; (d) 50 g l$^{-1}$.

Figure 12. XRD patterns of BSCCO films in different states.
concentration makes the deposition weight increasing, the resistance of the deposition film increasing, and the effective voltage of the suspension decreasing, which leads to a decrease in the subsequent deposition rate, so the deposition weight and the linearity of the suspension concentration is deviated.

Meanwhile, at high BSCCO concentration, there are high deposition rate and agglomeration of BSCCO particles, resulting in poor density of BSCCO films. Figure 11 presents the SEM morphology of the as-deposited film fabricated from the BSCCO suspension of different concentrations at same conditions ($V = 10\, \text{V}$, $t = 5\, \text{min}$), from which it can be seen that all the films are uniform and dense when the concentration of BSCCO suspension is above 20 g L$^{-1}$, while the BSCCO suspension is at a concentration of 10 g L$^{-1}$ resulted in a non-uniform film. Thus selecting a suspension with a concentration of 20 g L$^{-1}$ is enough to meet the requirements.

### 3.5. Superconductivity of sintered film

The XRD patterns of BSCCO films prepared in different states were measured, shown in figure 12. As BSCCO powders come into BSCCO precursor film by EPD, higher intensity Bi-2212 phase at (008), (0010) and (0012) peaks are detected, which indicates that c-axis orientation begins to appear through electrophoretic deposition process. Moreover, the intensities of Bi-2212 phase at (008), (0010) and (0012) peaks are higher while others are very low for the film heated at 820 °C for 20 h, indicating that high c-axis orientation is observed. At the same time, the intensity of the minor phase Ca$_2$PbO$_4$ decreases gradually when the BSCCO powders undergo the process from electrophoretic deposition to sintering.
The morphology of the as-deposited BSCCO film and sintered film fabricated under the optimal conditions (c = 20 g L\(^{-1}\), V = 10 V, t = 10 min) were observed, shown in figure 13, and it can be seen that after sintering (figure 13(b)), the surface of the film was uniformly smooth and almost homogeneous.

Figure 14 shows the R-T curve of the sintered film deposited by EPD with respect to suspension parameters. It can be seen from the figure that the critical temperature \(T_c\) of the sintered film obtained by the 20 g L\(^{-1}\) BSCCO suspension with I\(_2\) is 82 K and the \(\Delta T\) is 2 K. Therefore, the BSCCO film obtained under optimal conditions has a high \(T_c\), and the transition temperature range from normal to superconducting state is small.

4. Conclusions

In this work, a method for preparing BSCCO films by electrophoretic deposition with mild conditions and no damage on the structure of BSCCO powders is established, which lays the foundation for industrial production. It is concluded that the BSCCO suspension obtained by using isopropanol as the solvent and adding 0.08 mg mL\(^{-1}\) I\(_2\) is the best, and can prepare BSCCO films with better microstructure and performance. The addition of I\(_2\) can enhance the particle charge in the organic suspension by analyzing the data gathered from the zeta potential, pH and conductivity of the suspension. The analysis of the charging mechanism of BSCCO particle has certain significance for the formation of stable superconducting suspension. Through the study of the electrophoretic deposition kinetics, controlling the appropriate deposition time, deposition voltage and suspension concentration, a BSCCO film with controllable thickness can be obtained. These improvements reflect a high c-axis orientation, \(T_c\) of 82 K and sharp superconducting transition of BSCCO film.

Of course, the current work is mainly to obtain a stable suspension and the film with better microstructure. In future research, the critical temperature can be increased by optimizing the sintering process and studying the phase reaction mechanism to obtain a film with high purity of Bi-2223.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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