Influence of Annealing Temperature on the Structure and Performance of YBCO Thin Film on MgO Substrate

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Abstract. Annealing treatment is adopted for studying the changes of structure and low temperature superconducting performance of YBCO thin film on MgO Substrate. X-ray diffraction (XRD) analysis results show that c axis orientation of YBCO thin film is optimized with the rise of annealing temperature. It reaches the optimum value at 720 °C. The c axis orientation of YBCO thin film shows recession when the annealing temperature is higher than 720 °C. The change trend of increasing firstly and decreasing subsequently is also discovered with annealing temperature, the optimal critical current density value is obtained at about 730 °C. Research results show that the YBCO thin film structure and low temperature superconducting performance can be effectively improved through optimizing annealing temperature.

1. Introduction

YBCO high temperature superconducting thin film, as a superconducting material, has been a hot topic of research in the field of electronic materials. Its application has pushed the emergence of high temperature superconductor research upsurge within the world scope. Though the superconducting mechanism of YBCO high temperature superconducting thin film is not completely mastered by people from the perspective of material science, its research progress hereof in practical engineering application is not affected, and high temperature superconducting technology is rapidly developed into a technology and industry[1-3].

Because YBCO high temperature superconducting thin film has extremely low microwave surface resistance, the insulation substrate used for thin film growth belongs to monocrystal (100), which is consistent with the selection of materials during production of microwave passive components. Application of microwave passive components (such as filters, resonators, delay line, etc.) made of high temperature superconducting thin films in high sensitivity receiver front end and satellite communication ground receiving station, etc. is one of main application directions of current high temperature superconducting technology[4-6]. However, development of high-quality YBCO epitaxial thin films on low loss substrates (such as sapphire, LaAlO3 and MgO, etc.) is the key of the devices[7-8]. Therefore, the selection of the substrate is very important aiming at preparation of high-temperature superconducting thin films. MgO has a cubic crystal structure. Its lattice constant is a=4.21Å. Despite it has large lattice mismatch with YBCO, dielectric constants of MgO are isotropic, it has very low dielectric loss, which is very suitable for application of microwave devices. YBCO thin film prepared by MgO as the substrate can be used for preparing microwave passive devices with excellent performance. MgO is adopted as the substrate for settling YBCO thin films by pulsed laser
deposition, magnetron sputtering, thermal evaporation and E-beam evaporation, which has been reported. However, The YBCO thin film structure and performance with MgO thin film as substrate are lower than YBCO thin films prepared with other materials (such as LaAlO₃, etc.) as substrate due to lattice mismatch. The research shows that annealing is a fairly effective method to optimize YBCO structure and performance. In the paper, annealing method is adopted to study the influence of annealing temperature on structure and performance of YBCO thin films with MgO as the substrate.

2. Experiment
Self-developed high vacuum tube annealing furnace is adopted for carrying out annealing researching on YBCO thin films at the MgO substrate. The vacuum degree of the annealing furnace is up to 5×10⁻⁴ Pa. YBCO thin films are deposited by pulse laser deposition equipment. The applied substrate belongs to a (001) crystal orientation monocrystal MgO substrate. The dimension is 10mm×10mm. The thickness is 0.5mm. The selected target purity is higher than 99.95%. When PLD is used for plating YBCO thin films, MgO substrate temperature is 600 °C, oxygen pressure is stabilized at ~2.5mTorr. The deposited thin film undergoes high temperature annealing treatment. The annealing condition is divided into oxygen atmosphere annealing. The oxygen pressure is 1Torr, the annealing temperature is 650 °C ~ 800 °C, and the annealing time is 3h.

Philix X’PERT MPDX is adopted for XRD scanning. Thin film phase composition and thin film crystallographic orientation are analyzed. J-sacn Leipzig system is adopted for testing critical current density and the test condition is 77K.

3. Results and discussion
3.1. Influence of annealing temperature on YBCO thin film structure
We fix annealing pressure and annealing time process conditions, YBCO thin films are annealed under different temperature, and concrete process conditions are shown in table 1 in order to study the influence of annealing temperature on YBCO thin film structure at the MgO substrate, and explore appropriate annealing temperature parameters.

| Table 1. Annealing process parameters |
|-------------------------------|-----------------|-----------------|
| Sample number | Annealing temperature | Annealing atmosphere | Annealing time |
| S1 | 650°C | 1Torr | 3h |
| S2 | 700°C |  |
| S3 | 750°C |  |
| S4 | 800°C |  |

Figure 1 shows θ-2θ scanning spectra of growing YBCO thin films under different temperatures. When the annealing temperature is reduced to 650 °C, YBCO thin film grows at a-axis orientation. Micro small peak (005) (figure 1a) is available at 38 °. YBCO thin films are gradually changed from a-axis to c-axis orientation with the increase of temperature. The a-axis diffraction peak intensity is weaker and weaker, c-axis diffraction peak intensity is higher and higher, and c-axis preferred orientation is the best at 750 °C. The substrate temperature is increased continuously. When the temperature is increased to 800 °C, other orientation diffraction peak of YBCO thin film, non-YBCO diffraction peak and other impurity peaks appear in the thin film. The thin film may suffer from decomposition (figure 1d).

The c-axis orientation degree in the thin film is reflected by the size of FWHM. FWHM is smaller, c-axis orientation degree is higher, and the volume content occupied by grains in c-axis tilt direction. We conducted XRD ω scanning analysis on YBCO thin films (005) with higher c-axis preferred orientation. The scanning spectra is shown in figure 2. The FWHM of sample S1(650°C) and sample
S3(750°C) is similar, which is about 0.9° (figure 2a,c). However, it is much larger than the FWHM of the sample S2(700°C) (figure 2b). It is obvious that the annealing temperature has greater influence on YBCO thin film surface external orientation. When the substrate temperature is 750°C, although c-axis preferred orientation degree is high, a-axis grain is less, the volume content occupied by grains of the c-axis tilt orientation is still larger, and the FWHM is larger. FWHM is increased after 750°C. It is obvious that more and more grains grow away from c-axis. The FWHM of the sample S4(800°C) reaches 1.29° (figure 2d). It further illustrates that too high temperature is very unfavorable for thin film surface external orientation. The orientation degree of the thin film is the best at 700°C, and the FWHM is only 0.67°.

Figure 1. YBCO thin-film θ-2θ scanning spectra of annealing treatment at different temperatures.

Figure 2. YBCO thin-film ω scanning spectra of annealing treatment at different temperatures.
3.2. The influence of annealing temperature on YBCO thin film superconducting performance

S1 to S4 samples respectively undergo critical current density Jc tests. The influence of annealing on YBCO thin film performance is discussed. Main results are shown in table 2. When annealing temperature is 650 °C, Jc is 1.55 mA/cm². Jc is gradually increased with the increase of the annealing temperature. When the annealing temperature is 700 °C, Jc is 2.63 mA/cm². When the annealing temperature is increased to 750 °C, Jc reaches 2.93 mA/cm². The annealing temperature is continuously increased, Jc shows a trend of decrease, Jc is only 1.43mA/cm² at 800 °C. The change curve is shown in figure 3. The optimum annealing temperature of YBCO thin film on the MgO substrate is about 730°C by fitting curve. Jc size of YBCO thin films is changed with annealing temperature mainly because annealing leads to changes of YBCO thin film lattice orientation. Jc size change with the annealing temperature is basically consistent with the change of c-axis orientation grain proportion with the annealing temperature. It further proves that grain c axis orientation is the key for YBCO thin film to get excellent low temperature superconducting performance.

Table 2. YBCO thin film critical current density under different annealing temperatures

| Sample number | Annealing temperature | Critical current density (Jc, mA/cm²) |
|---------------|-----------------------|-------------------------------------|
| S1            | 650°C                 | 1.55                                |
| S2            | 700°C                 | 2.63                                |
| S3            | 750°C                 | 2.92                                |
| S4            | 800°C                 | 1.43                                |

Figure 3. Change curve of YBCO thin film critical current density with annealing temperature.

4. Conclusion
Annealing treatment is adopted for studying the changes of structure and low temperature superconducting performance of YBCO thin film at MgO substrate under different annealing temperatures. X-ray diffraction (XRD) analysis results show that c axis orientation of YBCO thin film is optimized with the rise of annealing temperature. It reaches the optimum value at 720 °C. The c-axis orientation of YBCO thin film shows recession when the annealing temperature is higher than 720 °C. Similar change laws are displayed in the test of low temperature critical current density. The change trend of increasing firstly and decreasing subsequently is also discovered with annealing temperature, the optimal critical current density value is obtained at about 730 °C. Research results show that the annealing temperature is one more sensitive physical quantity. The YBCO thin film structure and low
temperature superconducting performance can be effectively improved through optimizing annealing temperature.

References
[1] Avenhaus B, Porch A, Laneaster M J, et al. 1995 IEEE Transactions on Applied Superconductivity 2 1737.
[2] Chen M, Donzel L, Lakner M, et al. 2004 Journal of the European ceramic society 24 1815.
[3] Bagarinao K D, Yamsaki H, Nie J C, et al. 2005 IEEE Transactions on Applied Superconductivity 15 2962.
[4] Bindi M, Botarelli A, Gauzzi A, et al. 2004 Superconductor Science and Technology 17 512.
[5] Kim C J, Jun B H, Kim H J, et al. 2005 Physica C: Superconductivity and Its Applications 426 915.
[6] Ohshima S, Shirakawa M, Kitamura K, et al. 2004 Chinese Journal of Physics 42 425.
[7] Wang Y S, Guan X J, Zhang H Y, et al. 2010 Science China, Technological Sciences 53 2239.
[8] Wang L H, Shu Y H, Fan J 2012 Science China, Technological Sciences 55 1.