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The investigation of Sn diffusion on the magnetic levitation force performance of YBCO superconductors

S. B. Güner[1, *], Ş. Çelik[2]

[1]*Department of Physics, Faculty of Arts and Sciences, Recep Tayyip Erdoğan University, Rize, 53100, Türkiye*

[2]*Department of Energy Systems, Faculty of Engineering and Architecture, Sinop University, Sinop, 57000, Türkiye*

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ABSTRACT

This study has investigated the effect of tin (*Sn*) diffusion on structural, electrical and magnetic properties of the bulk $YBa_2Cu_3O_{7-x}$ (Y123 or YBCO) superconductors fabricated by a solid-state reaction method by X-ray Diffraction analysis (XRD) and the electrical resistance, but also the magnetic levitation force of tin (*Sn*) in the Y123 material for the first time. In this study, the samples were annealed for the diffusion at 900, 800, 700 and 600°C for 24 hours after the tin atoms evaporated on YBCO samples. From XRD patterns, pure and *Sn* diffused YBCO samples was found the orthorhombic YBCO phase structure peaks as (130), (010) and also (200) - (220) *Sn* peaks. Moreover, it is obtained from that the lattice parameter *a* and *c* are decreased with the increase of diffusion temperature. On electrical properties, *Sn* diffusion on YBCO samples decreased the critical transition temperature T^{offset}_c of YBCO from 87.3 K to 89.7 K. The magnetic levitation force measurements of the samples were performed under zero field cooling regimes at liquid nitrogen temperature to determine the effect of diffusion temperature of *Sn* in YBCO on the force.

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1. INTRODUCTION

Since their discovery, superconducting materials have been exploited in technological applications such as flywheels, motors, superconductive magnetic bearings, generators, permanent magnets, nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI), and magnetic levitation transportation systems as seen in Figure 1 [1-4]. The behavior of the superconductors in a magnetic field, generated by a permanent magnet (PM), has been used in most of applications. The repulsive force between the superconducting sample (SC) and the *PM* occurs because of the diamagnetic property of the superconductors. There are lots of parameters affecting the repulsive force, called magnetic levitation force, such as magnetic field, the distance between the *PM* and the *SC*, temperature, cooling distance between them, thickness of the sample, the radius of the sample, structure of the sample, the velocity of the permanent magnet or the sample, the critical current density (J_c) and shielding current loops which are related with the grain size. The most effective of these is the J_c and the induced shielding current loops of the sample which are directly dependent on the chemical and crystallographic structure of the material such as YBCO, BSCCO, MgB_2, etc. [5-19].

Up to now, many research groups have accomplished a lot of studies about superconductors for some levitation force measurements [20-30]. Magnetic fields capacity present to lift (levitate) block and can let an object to turn around a way with touchless movement. Superconducting materials show perfect conductor properties and indicate a great diamagnetic action [31]. Superconductor samples can supply passive magnetic lifting force and the stability is greatly increased by flux pinning centers and so a *PM* can stably levitate above a *SC*, Figure 2(a). A significant levitation show of a superconductor sample is a contactless movement of large objects or blocks, as indicated in Figure 2(b), the levitation of a sumo wrestler of around 200 kg in Tokyo, Japan. Today, using the remarkable magnetic levitation performance between the *PM* and *SC* over 1000 kg masses have been moved with a contactless effect. SupraTrans project, a prototype train, is a modernization carrying vehicles using magnetic levitation performance, Dresden, Germany, as shown in Figure 2(c) [31].

Fig. 1. Superconducting technological applications [1-9].

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*Corresponding author e-mail: sbaris.guner@erdogan.edu.tr

Fig. 2. (a) PM levitated over an SC [14], (b) The levitation of sumo, (c) SupraTrans project, a prototype train, is a modernization carrying vehicle using magnetic levitation performance, Dresden, Germany [31].

Although the single crystalline superconducting sample has a higher critical current density than a polycrystalline sample, the fabrication processes are very difficult and sensitive to thermal processes. Moreover, the J_c of the polycrystalline samples can be increased with the strong interaction between the grains in the polycrystalline superconducting structure. In our previous study, *Yb211* addition in Sm123 structure showed us that *Yb211* structure behaved as the welding material between *Y123* grains and resulted in an increase in the magnetic levitation force which originated from the increase in J_c [32], *Gd* diffusion in *Y123* [33], *Yb* diffusion in *Y123* [34], *Gd* and *Yb* substitution to *Y* in *Y123* [35], were studied. On the other hand, the induced shielding current loops can be increased by the artificial strong pinning centers. Moreover; according to the references [36] and [37] about the tin (*Sn*) diffusion on YBCO samples, the presence of *Sn* ions in the bulk $YBa_2Cu_3O_{7-x}$ superconductors is due to the broadening of the resistive transition enhanced as a result of the decrement of the crystallinity and grain connectivity.

In this work, we have worked the influence of diffusion temperature between 600-900 °C of *Sn* in YBCO on the magnetic levitation force, which is corresponding to the J_c and the induced shielding current loops, at liquid nitrogen temperature using the homemade magnetic levitation force system. At this point diffused *Sn* in *Y123* structure is thought to behave as good artificial pinning centers and result in a rise in the J_c.

2. EXPERIMENTAL

Superconducting $YBa_2Cu_3O_{7-x}$ samples with a density between 4 g/cm3 were fabricated by the solid-state reaction method. The weighed powders of Y_2O_3, $BaCO_3$, and CuO were mixed and milled for 4 h in a gate mortar. After milling, the mixed powders were calcined at 940 °C for 24 h in air. The heating and cooling temperature rates were estimated as 2 and 1 °C/min, respectively. After a calcination process, the sample was grounded and pressed under 270 MPa into pellets with a diameter of 13 mm. The pellets were sintered at 945 °C for 24 h and then cooled to room temperature under oxygen flow. The *Sn* was evaporated on the pellets (thickness of about 10 μm) in the vacuum chamber under the pressure of $2x10^{-7}$ Torr as seen in Figure 3. After the evaporation, the diffusion annealing process was performed at the temperatures such as 900, 800, 700, and 600 °C for 24 h (these samples will be named T900, T800, T700, and T600, respectively) in flowing oxygen.

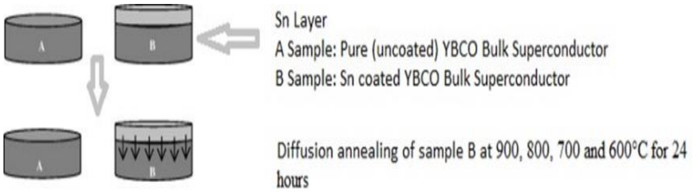

Fig. 3. Schematic representation of the sample-coated fabrication stage.

The microstructure properties of the YBCO samples were worked by the X-ray Diffraction (XRD) a Rigaku Smart Lab diffractometer with wavelength 1.5405 Å analysis. By using XRD patterns, the lattice parameters were calculated.

The electrical resistivity versus temperature between 60–130 K is measured by a standard DC four-probe contact technique by a closed-cycle cryostat. Both current and voltage connections are made with silver paint to diminish contact resistance. A temperature value, where the resistivity goes up to decrease significantly, is performed to be the onset critical transition temperature of the *SC* while the offset transition temperature (T^{offset}_c) is determined as the temperature at which R = 0 Ω.

The magnetic levitation force measurements were made in air at liquid nitrogen temperature by using the cylindrical permanent (*NdFeB*) magnet, whose diameter and height are 12.68 mm and 9.58 mm respectively, in homemade system as seen in Figure 4. In this experiment, the permanent magnet (PM) was fixed and the superconducting sample moved. After the sample was cooled at the cooling height which is 50 mm far from the permanent magnet in the axial direction, the superconducting sample (SS) in liquid nitrogen was moved towards and then away from *PM* with a constant velocity (1.96 mm/s) in the axial direction. The vertical magnetic levitation force between PM and SS was continuously measured by sensitive balance whose capacity is 220 g, and then divided by the sample volume to calculate magnetic levitation force density (LFD). The motion of the sample was performed by the stepper motor in micro-step mode, and also the position was measured by the displacement sensor. The force measurement system was controlled by the software. The cooling *zcr* (zero cooling regime) and the z_{min} (z-axis minimum distance) between the top surface of *PM* and the bottom surface of SS were selected to be 50 mm and 1 mm, respectively as seen in Figure 5.

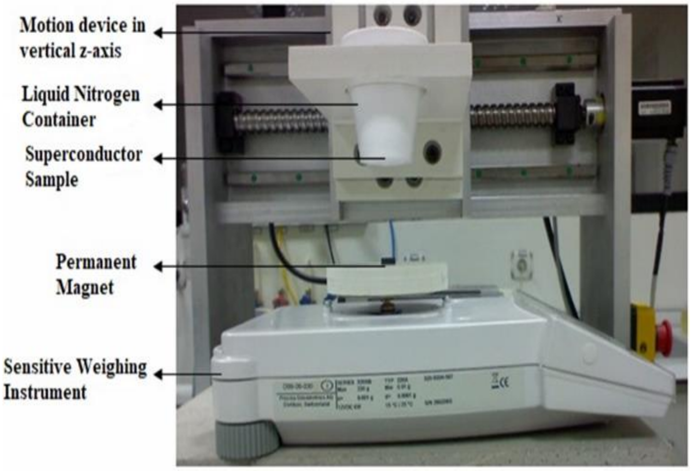

Fig. 4. Magnetic levitation force measurement system.

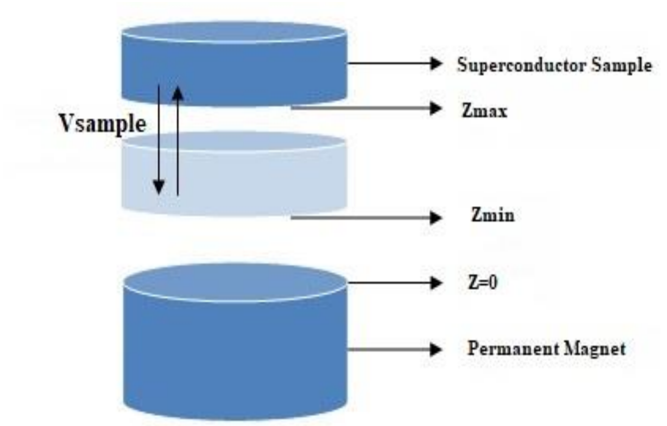

Fig. 5. Schematic representation of the sample motion of the distance relationship between the superconducting sample and the permanent magnet during magnetic levitation measurement.

3. RESULTS

The XRD patterns (2θ=20-60º) of pure and tin (*Sn*) diffused annealed YBCO bulks at 600, 700, 800, and 900 °C for 24 h were shown in Figure 6. Pure and Sn diffused *YBCO* samples found the orthorhombic YBCO phase structure peaks as (030), (001), (123), (021), (130), (010), (111), (121), (050), (131), (006), (200), (151), (061), (032), (070), (101) and (132). Also, T600, T 700, T800, *and* T900 sample was observed (200) and (220) *Sn* peaks. Just T900 sample was seen (101) *Sn*. These results were consistent with the ref. [35, 38].

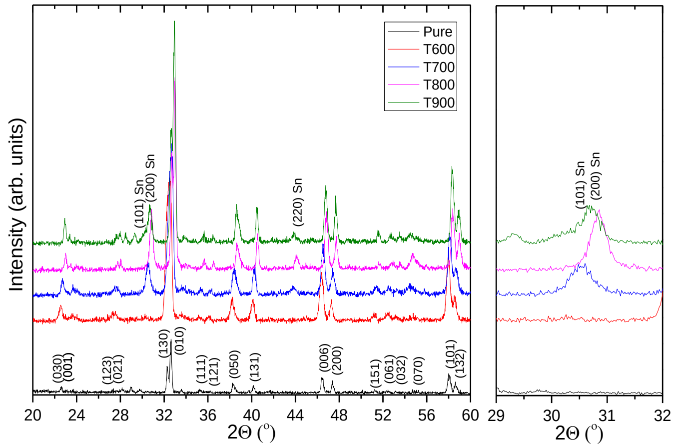

Fig. 6. XRD patterns of the pure and *Sn* diffused samples at the temperature of 600, 700, 800, and 900 °C by *Sn* for 24 h.

Figure 7 shows the *a* and *c* lattice parameters of pure YBCO and T600, T700, T800, and T900 YBCO samples calculated by using XRD patterns. The lattice parameters of pure and T600, T700, T800, and T900 samples were found as 3.842, 3.83436, 3.82828, 3.81012, and 3.80712 Å, respectively. On the other hand, the *c* lattice parameters of pure and T600, T700, T800, and T900 samples were obtained as 11.72262, 11.71788, 11.69412, 11.63748 and 11.62344 Å, respectively. From the XRD patterns of the T600 sample to that of T900, the XRD curves slide to the right slightly. As a result of this, the lattice parameters *a* and *c* are decreased with the increase of diffusion temperature as shown in Figure 7. Because the bonding radius of *Sn* (158 pm) is smaller than that of *Y* (182 pm) and *Ba* (224 pm) atoms [35] substitution diffusion between *Y/Ba* and *Sn* decreased the lattice parameter with the increasing diffusion temperature.

In this work, the electrical resistance as a function of temperature curves for all the samples is performed between 70 to 120 K, and results are indicated in Figure 8. It is clear that the curves from Figure 8 show a transition temperature below the superconducting offset temperature (T^{offset}_{c}) for the superconducting state. *Sn* diffusion not only decreased the normal state resistivity but also decreased the critical transition temperature T^{offset}_{c} of YBCO from 89.7 K to 87.3 K. This result is consistent with reference [39]. The superconducting transition temperature range (ΔT) increases in doped samples compared with the pure sample as illustrated in Figure 8. The reason for the increase is the existence of tin ions in the YBCO bulk superconductors owing to the widening of the transition temperature and this case improves the decrement of the grain connectivity and crystallinity [40, 41].

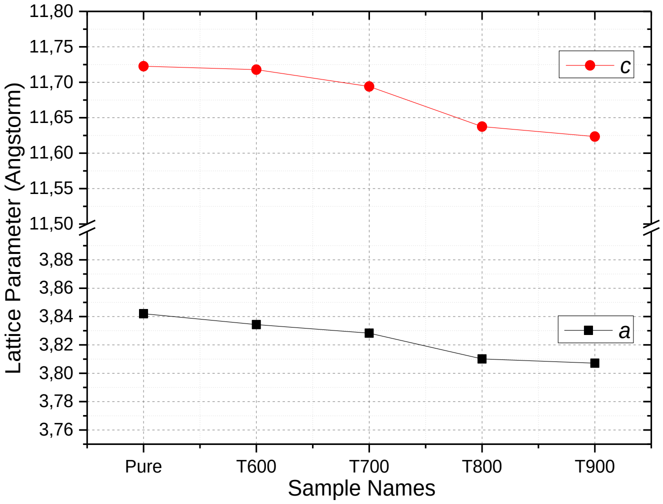

Fig. 7. Temperature dependence of *a* and *c* lattice parameters for the *Sn* diffusion in *YBCO* samples annealed at 600, 700, and 900º C for 24 h.

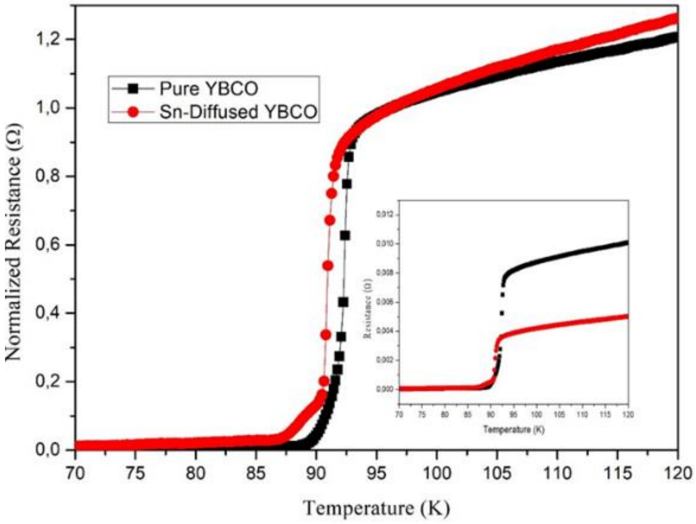

Fig. 8. Temperature dependence of normalized resistance pure *YBCO* and *Sn*-diffused *YBCO*. The inset is the resistance as a function of temperature curves for the same samples.

As known in the literature, the magnetic levitation force between a permanent magnet (PM) and a superconductor (SC) is dependent on the magnetic field gradient of the *PM* and the magnetic moment of the superconductor, therefore the levitation force is calculated by using $F=m(dH/dz)$. dH/dz is the magnetic field by the PM and m is the magnetic moment of SC which is related with the shielding current and J_c. The superconductor magnetization is $M = AJ_cr$, where the A is constant depending on the sample geometry, J_c is the critical current density of a superconductor, r is the radius of a shielding current loop, and magnetization per unit volume (V) is defined as $m = MV$ [42, 43]. This equation shows that it is essential to supply r, J_c (which rises with the increasing amount of pinning centers in the SC), and dH/dz as high as a potential to obtain a strong magnetic levitation force performance. In this work, magnetic levitation force measurements were made under a zero-field cooling regime. Figure 9 shows the maximum magnetic levitation force density (mN/mm^3) at the minimum distance between e top surface of the cylindrical shape permanent magnet and the bottom surface of the superconductor sample.

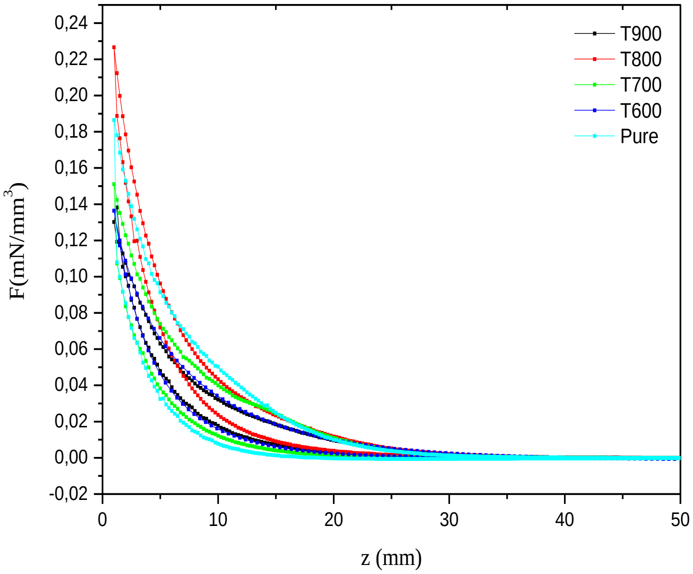

Fig. 9. Magnetic levitation force density of the sample which was diffused *Sn* at 600, 700, 800, and 900 °C versus the distance *z* between the bottom surface of the sample and the top surface of the permanent magnet while the sample was moving.

Figure 10 shows the maximum magnetic levitation force data versus samples. The maximum magnetic levitation forces of pure and T600, T700, T800, and T900 samples were obtained as 0.19, 0.14, 0.15, 0.23, and 0.13 respectively. As shown in Figure 10; when the *Sn* diffusion temperature rises from 600 to 800, the maximum magnetic levitation force values increase from 0.14 N to 0.23 N. Then with the T900 sample, the magnetic levitation force decreased to 0.13 N. The maximum levitation force value of the pure YBCO sample was found as 0.19 N. It is observed that the optimum *Sn* diffusion on *YBCO* samples for strong maximum levitation force is 800 °C for 24 h. One of the most important parameters affecting the magnetic levitation force is the critical current density. It is considered that the reason for the high magnetic levitation force having a T800 sample is the source of critical current density. Choi et al. found that the value of critical current densities at 77 K and 67 K of *Sn*-doped YBCO samples are higher than pure YBCO samples [44, 45]. As analyzed by our levitation force data magnetic levitation force results of *Sn* diffused YBCO sample is consistent with *Sn* doped YBCO sample. These values are also comparably below that of pure YBCO. The differences in the magnetic levitation force density at the same position between moving of sample towards to and from the permanent magnet is the maximum at the diffusion temperature of 800 °C. This can be thought that *Sn* diffusion is effective not only between grains but also intergrains of polycrystalline *Y123* sample. On the other hand, the diffusion temperature of 900 °C is effective in inter and intragrains, but this effect decomposed the structure between grains into the non-superconducting structure. This resulted in a decrease in the magnetic levitation force density of the sample diffused at the temperature of 900 °C.

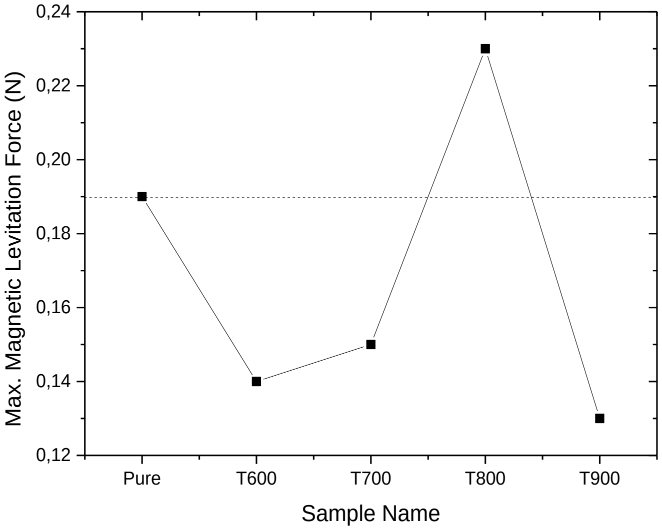

Fig. 10. The maximum magnetic levitation force versus samples.

4. CONCLUSIONS

This work has studied the influences of *Sn* diffusion on YBCO bulks fabricated by a solid-state reaction method by X-ray Diffraction analysis (XRD) and the electrical resistance and worked also the magnetic levitation force of tin (*Sn*) in the *Y123* material for the first time. From XRD patterns, pure and *Sn* diffused YBCO samples were obtained as the orthorhombic YBCO phase structure peaks with (130), (010), and also (200) - (220) *Sn* peaks. Moreover, it is calculated that the lattice parameter *a* and *c* by using (006) and (200) peaks are decreased with the increase of diffusion temperature. On electrical properties, *Sn* diffusion on YBCO samples dropped the critical transition temperature T^{offset}_c of YBCO from 89.7 K to 87.3 K. Moreover, the presence of *Sn* ions in the bulk $YBa_2Cu_3O_{7-x}$ superconductors enhances as a result of the decrement of the crystallinity and grain connectivity. The magnetic levitation force measurements of the samples were performed under zero-field cooling regimes at liquid nitrogen temperature to suspect the effect of diffusion temperature of *Sn* in YBCO on the force. The maximum magnetic levitation forces of pure and T600, T700, T800, and T900 samples were obtained as 0.19, 0.14, 0.15, 0.23, and 0.13 respectively. This study is supplied to assist with the superconductor magnetic levitation performances of different diffusion materials of *(RE)BCO* (*RE=Nd*, *Sm*, *Gd* and *Er*).

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Biographies

Sait Barış Güner is an associate professor at Recep Tayyip Erdoğan University. He obtained his Ph.D. in Physics Department at the same university in 2017. He is specialized in the fabrication and characterization of single and multi-seeded YBCO samples. He has received several awards for his academic work. His main topic focuses on the magnetic levitation force of superconductor samples and the fabrication of high and low T_c superconductor samples. She is the author of several international publications and scientific papers.

E-mail: sbaris.guner@erdogan.edu.tr

Şükrü Çelik is a professor at Sinop University. He obtained his Ph.D. at the Karadeniz Technical University in 2006. He is specialized in the fabrication and characterization of *MgB2* and *(RE)BCO* samples and has defended several Master and Ph.D. theses. He has participated in many remarkable academic projects. His main topic focuses on cryostats, cryogenic systems, machine control by LabVIEW, MATLAB etc., the magnetic levitation force of superconductor samples, and the fabrication of high and low Tc superconductor samples. He is the author of many international respectable publications and scientific papers.

E-mail: sukrucelik@yahoo.com