Study of localization processes in transport properties of Bi:2201 epitaxial thin film

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Epitaxial Bi:2201 thin films were deposited on $SrTiO_3$ (100) substrate using the DC magnetron sputtering method. Optimal deposition conditions for superconducting films with smooth film surface and high epitaxial quality were obtained. The effect of partial oxygen pressure (f_{O2}) in sputtering gas on the electrical resistivity was studied. The phase diagram for transition temperature and localization temperature function of oxygen partial pressure was obtained.

1. Introduction

Since the discovery of high-T_c superconductors of $Bi_2Sr_2Ca_{n-1}Cu_nO_{2(n+2)+\delta}$ (n=1,2,3), intensive studies of these compounds have been carried out.

The $Bi_2Sr_2Ca_{n-1}Cu_nO_{2(n+2)+\delta}$ high temperature superconductors (HTS) is very important for fundamental investigations and technical applications. $Bi_2Sr_2Ca_{n-1}Cu_nO_{2(n+2)+\delta}$ (BSCCO) has high critical temperatures ($T_c \sim 20K$ for n=1, $T_c \sim 85K$ for n=2 and $T_c \sim 110$ K for n=3) and high critical current densities at low temperature and is used for the fabrication of long lengths HTS tapes.

The strong anisotropy of this compounds and the easy intergrowth of different phases has challenged several groups to grow films with well-oriented and single-phase structure.

Different techniques such as molecular beam epitaxy (MBE), metal-organic chemical vapor deposition (MOCVD), DC and RF sputtering, liquid phase epitaxy (LPE) and pulsed-laser deposition (PLD) have been employed [1].

Bi:2201 epitaxially thin films grown by RF sputtering on a $SiTiO_3$ substrate at T_c=9 K presents a clear nonmetallic upturn near the superconducting transition [2].

The Bi:2201 superconductor is found to have a large residual resistivity [3]. This indicates the presence of strong scatterers of charge carriers in the CuO_2 planes. A vacancy in the CuO_2 plane is expected to act as a nonmagnetic potential scatterer, just like the Zn impurity in planes. These vacancies may be caused by expelling interstitial oxygen atoms after the vacuum annealing or after some thermal treatments.

By controlling the oxygen concentration δ (by successive annealing treatments of $Bi_2Sr_{1.6}La_{0.4}CuO_{6+\delta}$) the same film is changed from overdoped to strongly underdoped state [4]. As a result the electrical resistivity is changed from T-linear behavior (optimal doping) to insulating behavior. Similarly results were obtained by the control of oxygen concentration in the sputtering gas [5].

Here we present results the structural properties and electrical resistivity of c-axis oriented epitaxial Bi:2201 thin films deposited onto $SrTiO_3$ substrates using the DC magnetron sputtering method. The effect of oxygen concentration in the sputtering gas on the temperature dependence of electrical resistivity is presented.

2. Experimental

Bi:2201 thin films were deposited onto heated single crystal $SrTiO_3$ substrates by using an inverted cylindrical DC magnetron for the sputtering. An off-stoichiometric target with a nominal composition Bi:Sr:Cu = 2.1:1.95:1.05 was home made by a solid state reaction method. The sputtering gas was a mixture of oxygen and argon with different partial pressure ratio f_{O2} /f_{Ar} in the range 0.5/0.5 to 0.35/0.65.

The deposition pressure was 1mbar for all samples. Sputtering was carried out in DC mode with a power of 25W. Before each deposition the target was presputtered for 30 minutes. The substrate temperature was kept at 720 ^{0}C (an optimized temperature regarding the epitaxial and compositional properties of the films), for all depositions in this study.

After deposition, the films were annealed at 500 ^{o}C in an oxygen atmosphere (1 mbar). The deposition time was 1 h, leading to nanoscale thin films with thickness of approximately 100 nm.

The films are chemically patterned and equipped with silver sputtered contacts pads. The temperature dependence of the in-plane resistivity is measured by using a standard four probe dc method.

3. Results and discussion

Fig. 1 shows the temperature dependence of electrical resistivity function of temperature, $\rho(T)$, for overdoped, optimal doping and underdoped thin films, obtained for values of $0.45 \le f_{O2} \le 0.60$ in sputtering gas.

The $\rho(T)$ dependence changed drastically function of f_{O2} and the superconductivity of Bi:2201 is very sensitive to the concentration of oxygen in sputtering gas. The room temperature resistivity increases monotonically with

decreasing f_{O2}.

For $f_{O2} = 0.6$, electrical resistivty develops a positive curvature, and is described by the law:

$\rho = \rho_0 + b \, T^m$,

with m=1.1.

This behavior characterize the film in overdoped region with a critical transition temperature T_c=9 K. The transition temperature T_c is estimated from electrical resistivity measurement by using the midpoint method. By decreasing the oxygen fraction to $f_{O2} = 0.58$, the electrical resistivity of the film shows above 60 K a linear temperature dependence (m=1) with the slope b= 1.25 $\mu\Omega$ cm/K and $\rho_0 = 0.14$ mΩ cm. This film shows the maximum value of critical transition temperature $T_{c \, max}$ =9.6 K, which correspond to a state near the optimum doping.
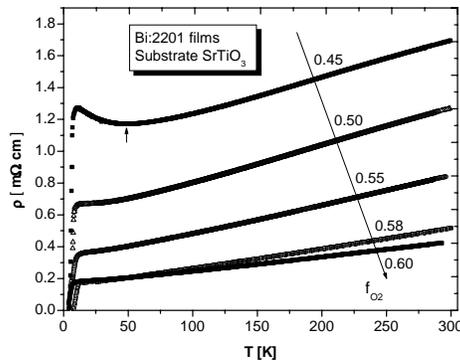

Fig. 1. The temperature dependence of electrical resistivity of Bi:2201 films and its variation with the oxygen fraction $0 .45 \leq f_{O2} \leq 0.60$ f_{O2} in the sputtering gas, The minimum in $\rho(T)$ is indicated by vertical arrow for $f_{O2}=0.45$ thin film.

With decreasing carrier concentration (by decreasing f_{O2} up to 0.50) the electrical resistivity shows an upturn before the transition in superconducting state and Tc decrease (Fig. 2). In our samples, the Sr deficiency and the f_{O2} in the sputtering gas control the range of variation for the oxygen content and the critical transition temperature, respectively.
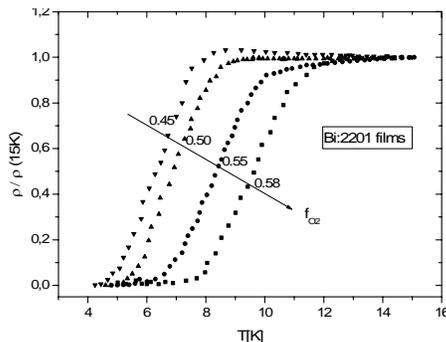

Fig. 2. The temperature dependence of electrical resistance for our Bi:2201 thin films in transition region.

Due to the difficulty in determination of oxygen doping (p) in Bi:2201 thin films, we represent the phase diagram as a function of doping state p by his equivalent $(\sigma/\sigma_{op})_{300K}$ (were σ_{op} is the conductivity for optimal doping). In has been shown that it exist a linear dependence of $(n_H)_{300K}$ (Hall number) or $(\sigma/\sigma_{op})_{300K}$ and the number p of holes per Cu [4]. For our studies, $(\sigma_{op})_{300}$ is the conductivity of the thin film obtained for f_{O2}=0.58.

Fig. 3 shows that the critical temperature is a parabolic function of (σ/σ_{op}), in agreement by the empirical parabolic function: $T_c / T_{cmax} = 1 - 82.6(p-0.16)^2$ [6].
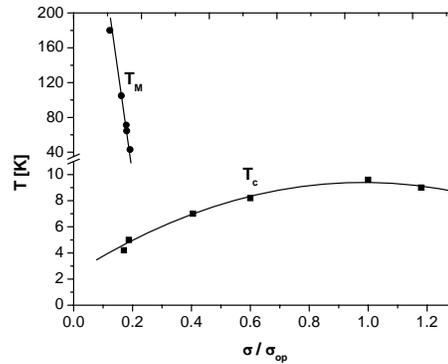

Fig. 3. Schematic phase diagram of Bi:2201 films as a function of the parameter $(\sigma/\sigma_{op})_{300K}$, showing the superconducting Tc (open square) and the localization temperature T_M (open circles).

The quantity (σ/σ_{op}) is used in order to parametrize the doping level of the strongly underdoped states (Tc=0), where the parabolic variation cannot be applied. Fig. 3 shows the phase diagram of Bi:2201 thin films. The superconducting transition temperature T_c and the localization temperature T_M (when appear the insulator behavior, where $\rho(T)$ is minim) are plotted versus the (σ/σ_{op}).

In Fig. 3 the localization temperature T_M shows a linear dependence versus $(\sigma/\sigma_{op})_{300K}$. The solid line characterizes the boundary between the insulating and metallic regimes. The extrapolated value of $T_M(\sigma/\sigma_{op})$ at zero temperature (T_M=0) is around (σ/σ_{op})=0.21, which correspond to p = 0.094 [4]. This value is near p=1/8, in agreement by the metal-insulator (MI) boundary deduced from $\rho(T)$ of BSLCO single crystal [7].

4. Conclusions

Epitaxial Bi:2201 thin films were deposited in situ onto SrTiO$_3$ substrate by DC magnetron sputtering by using different partial oxygen pressures (f_{O2}) in the sputtering gas.

By decreasing f_{O2}, $\rho(T)$ changed drastically from optimally doped to underdoped regime.

The maximum value of critical transition temperature $T_{c \, max}$ =9.6 K, correspond to a state near the optimum doping (for $f_{O2} = 0.58$).

The temperature T_M for the $\rho(T)$ minimum (insulating behavior) increases by decreasing f_{O2}. The extrapolated

value of $T_M(\sigma/\sigma_{op})$ lies well inside of underdoped regime

  The critical temperature is a parabolic function of (σ/σ_{op}), in agreement by the empirical parabolic function $T_c / T_{c\,max}$ function of concentration carriers, p.

Acknowledgments

References

[1] R. Rossler, J.D. Pedarning, Ch. Jooss, Physica C **361** 13-21 (2001).

[2] C. Capan, K. Behnia, Z. Z. Li, H. Raffy, C. Marin, Phys. Rev. B **67**, 100507 (R) (2003).

[3] Y. Ando, G. S. Boebinger, A. Passner, N. L. Wang, C. Geibel, F. Steglich, Phys. Rev. Lett. **77**, 2065 (1996).

[4] Z. Konstantinovic, Z. Z. Li, H. Raffy, Physica C **351**, 163 (2001).

[5] A. V. Pop, G. Ilonca, M. Pop, D. Marconi, Physica C **460–462**, 817–818 (2007).

[6] M. R. Presland, Physica C**176**, 95 (1991).

[7] S. Ono, Y. Ando, T. Murayama, F. F. Balakirev, J. B. Betts, G.S. Boebinger, Physica C **138**, 357-360 (2001).

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