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The microwave response of MgB_2 /Al_2O_3 superconducting thin films*

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Microwave characteristics of MgB_2/Al_2O_3 superconducting thin films were investigated by coplanar resonator technique. The thin films studied have different grain sizes resulting from different growth techniques. The experimental results can be described very well by a grain-size model which combines coplanar resonator theory and Josephson junction network model. It was found that the penetration depth and surface resistance of thin films with smaller grain sizes are larger than those of thin films with larger grain sizes.

Keywords: MgB_2/Al_2O_3 thin films, surface resistance, penetration depth, grain-size model
PACC: 6460, 6150C, 7870G

1. Introduction

The discovery of superconductor MgB_2 with a critical temperature T_c about 39 K caused excitement in the solid state physics community[1−4] because it introduced a new, simple inorganic superconductor having a record high T_c for a non-oxide and non-C_{60} compound. MgB_2 is considered a promising material for replacing the conventional superconducting materials used in high-frequency electronic devices. Since the discovery of its superconducting properties, there has been very rapid progress in understanding the band structure of MgB_2 and double gap nature of superconductivity, in terms of both theory and experiment. Theoretical studies suggested that MgB_2 possesses two distinct superconducting gaps associated with two disconnected sheets of the Fermi surface,[5−8] resulting in a variation of gap values with the direction of the wave vector $\boldsymbol{k}$, which was very soon validified by reproducible results of tunnelling spectroscopy, point-contact spectroscopy and specific heat measurement.

The MgB_2 is important because of practical reasons. First of all, MgB_2 consists of light, cheap elements and possesses a simple hexagonal crystal structure, where the boron atoms form graphite-like sheets separated by hexagonal layers. Unlike other superconductors, there are no complications as a result of d-or f-electrons and no structural phase transition. All these make it an ideal system to understand how superconductivity occurs at such a relatively high temperature in such a simple system. Secondly, it is a very good material where there is no high contact resistance between grains. Weak link may not be thought of for high-quality MgB_2 thin films, because MgB_2 superconducting materials have longer coherence length than cuprate superconductors. The conduction electron density and normal-state conductivity of MgB_2 are one to two orders of magnitude higher than those of the cuprates. These features combined with the low cost, light-weight and easy fabrication of wires and thin films, make MgB_2 attractive for many applications. For electronic applications based on Josephson junctions, high quality thin films are of special importance. Efforts have been made on the growth of MgB_2 thin films[9,10] and two main types of techniques, i.e., ex-situ and in-situ methods, have been

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developed.[11−15]

At present, many kinds of resonators have been used to measure microwave characteristics of superconducting thin films, such as open-ended dielectric resonator, parallel plate resonator, cavity resonator, coplanar resonator, microstrip resonator, etc. The advantages of using coplanar structures are obvious, such as that only single sided superconducting film is required, which eliminates the complication of making double sided films. They also have the advantage of a wide range of characteristic impedances available regardless of the thickness of the substrate, and these structures can be easily connected to external circuit, etc.

In this paper, microwave properties of two samples of superconducting MgB_2/Al_2O_3 thin films, denoted respectively by sample #1 and sample #2 hereafter, are measured by coplanar resonator technique. They have different qualities and grain sizes, resulting from different growth techniques. A grain-size model which combines coplanar resonator theory and Josephson junction network model is used to analyze the penetration depth and microwave surface resistance of them.

2. The grain-size model

In the standard theory of distributed element transmission line resonator, the resonant frequency is given by $f_0 = \dfrac{1}{\lambda_1\sqrt{L(\lambda_e)C}}$, where λ_1 is the resonator's guide wavelength ($\lambda_1 = 2l$, l being the length of the central strip of the coplanar resonator) and $\lambda_e(T)$ is the effective penetration depth, $L(\lambda_e)$ is the total inductance per unit length, C is the capacitance of the line. In the case of superconducting coplanar transmission lines, $L(\lambda_e)$ is the sum of the geometric inductance L^g and the kinetic inductance $L^k(\lambda_e)$, namely $L(\lambda_e) = L^g + L^k(\lambda_e)$. If assuming the capacitance C of the line does not change significantly with temperatures, we can obtain an equation

$$\frac{f_0(T)}{f_0(T_0)} = \sqrt{\frac{L^g + L^k(\lambda_e(T_0))}{L^g + L^k(\lambda_e(T))}}, \tag{1}$$

where T_0 usually denotes the lowest temperature among the experimental data. The geometric inductance L^g is determined by the geometry of the line. The kinetic inductance $L^k(\lambda_e)$ is determined by the transport properties of the charge carriers of the transmission line and depends on the surface current density distribution across the conductor. The propagation characteristics can be deduced analytically by conformal mapping, resulting in the inductance per unit length[16−19]

$$L^g = \frac{\mu_0 M\left(\sqrt{1-(w/a)^2}\right)}{4M(w/a)}, \tag{2}$$

where M is the complete elliptic integral of the first kind, μ_0 is the vacuum permeability, w is the width of central strip line of coplanar resonator, and $a = w+2s$, with s being the spacing between the central strip and the ground; and the kinetic inductance

$$L^k(\lambda_e) = \frac{\mu_0\lambda_e^2(A_1 + A_2)}{wt}, \tag{3}$$

where t is the thickness of superconducting films, and

$$A_1 = \frac{2}{[M(w/a)]^2[1-(w/a)^2]}\left[1 + 0.25\ln\left(\frac{wt}{2\lambda_e^2(T)} - 1\right) - (w/4a)\ln\left(\frac{at + wt - 4\lambda_e^2(T)}{at - wt + 4\lambda_e^2(T)}\right)\right], \tag{4}$$

$$A_2 = \frac{2w/a}{[M(w/a)]^2[1-(w/a)^2]}\left[1 + 0.25\ln\left(\frac{at}{2\lambda_e^2(T)} + 1\right) - (a/4w)\ln\left(\frac{at + wt - 4\lambda_e^2(T)}{at - wt + 2\lambda_e^2(T)}\right)\right]. \tag{5}$$

In this paper, a grain-size model is suggested to analyze the microwave properties of superconducting thin films. In this model, the superconductor is treated as an effective medium consisting of two subsystems, namely the grains and grain boundaries. The basic circuit element of this model is a Josephson junction in series with individual grains, as shown in Fig.1. The microwave currents are confined to the profile of the penetration depth into the grains (λ_g) and grain boundaries (λ_J) as the dashed curves show in Fig.1. The most important parameters determining λ_J are the effective grain size b, critical current density J_c and the shunted resistance of the junction R_J. The whole film is then treated as a network of weakly cou-

pled grains. Hylton *et al*[20] pointed out that the microwave properties of such a film can be characterized by an effective penetration depth due to the reactance of the grains and the grain boundaries, and it turns out that

$$\lambda_e = \sqrt{\lambda_J^2 + \lambda_g^2}. \tag{6}$$

Here, λ_g is given by[16]

$$\lambda_g/\lambda_{g0} = 1/\sqrt{1-(T/T_c)^4}, \tag{7}$$

where λ_{g0} is the penetration depth of superconducting grains at 0 K, and λ_J is expressed as[19]

$$\begin{aligned}\lambda_J = & \sqrt{\frac{\hbar}{2ebJ_c\mu_0}} = \sqrt{\frac{\hbar}{2ebJ_{c0}\mu_0}} \Big/ \sqrt{1-\left(\frac{T}{T_c}\right)^n} \\ = & \lambda_{J0} \Big/ \sqrt{1-\left(\frac{T}{T_c}\right)^n},\end{aligned} \tag{8}$$

with n being a parameter which is related to the quality of the thin films, b the grain size of superconducting films, $2e$ the charge of superconducting electrons, $\hbar$ the Planck constant, and μ_0 the vacuum permeability. J_{c0} and J_c are the critical current densities of the films at 0K and at measuring temperature T, respectively; λ_{J0} is the penetration depth of grain boundaries at 0K. Combining the coplanar resonator theory and the Beasley's Josephson junction network model by putting λ_e given by Eq.(6) into Eq.(3), the parameters λ_{J0} and n can be deduced.

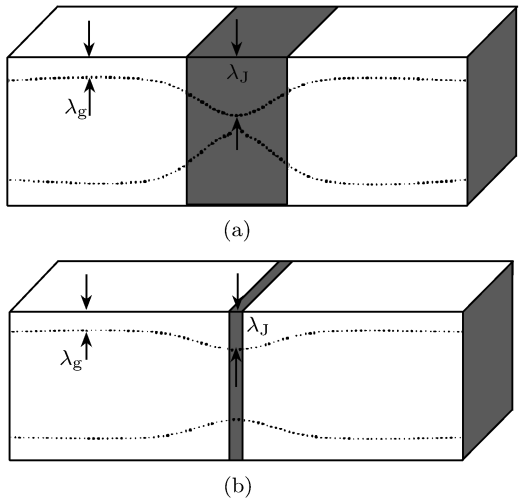


Fig.1. A grain-size model. Microwave characteristics of MgB_2/Al_2O_3 film sample #1 with small grain sizes can be described by Fig.1(a). For the MgB_2/Al_2O_3 film sample #2 with large grain sizes, Fig.1(b) may describe its microwave properties. λ_g is the grain penetration depth, λ_J is the grain boundary penetration depth, $\lambda_e = \sqrt{\lambda_g^2 + \lambda_J^2}$ is the effective penetration depth.

In the grain-size model, if $\lambda_g \gg \lambda_J$ then $\lambda_e \approx \lambda_g$, the properties of the superconducting thin films are dominated by grains. If $\lambda_g \ll \lambda_J$ then $\lambda_e \approx \lambda_J$, the properties of superconducting thin films are then dominated by grain boundaries. If the penetration depth of grains λ_g is comparable with the penetration depth of grain boundaries λ_J, properties of the thin films are determined by both grains and grain boundaries.

The surface resistance of superconducting thin films from coplanar resonator theory is determined as[18]

$$R_s = \frac{\omega L(\lambda_e) w}{Q_u(A_1 + A_2)}, \tag{9}$$

where $\omega = 2\pi f_0$, Q_u is the unloaded quality factor of the resonator. The surface resistance is dominated by the grain boundaries if the grain sizes or the critical current density J_c is small, making λ_e to approach λ_J. Whereas if the critical current density J_c is large, λ_e approaches λ_g, and the surface resistance is then dominated by the grains.

3. Experiments

The film sample #1 was deposited by pulsed laser. In the preparation of the in-situ annealed film, the precursor film were deposited on Al_2O_3 substrate from a stoichiometric MgB_2 target, the target-to-substrate distance was 3 mm. The deposition time was 12 min with a laser frequency of 8 GHz. During the deposition, the substrates were kept at 200 °C in argon atmosphere at pressure between 2×10^{-5} Pa and 4×10^{-5} Pa. Mg cap layer was then deposited onto the precursor film under the same conditions. The MgB_2/Al_2O_3 thin film was annealed in 15 Pa argon atmosphere. The heater was heated to 580 °C–650 °C and maintained at that temperature for 5–15min. For the ex-situ annealed film sample #2, Mg and B were deposited by e-beam on Al_2O_3 substrate. The substrate were kept at 27 °C. The precursor film was then put into a Ta box and sealed in the tube in Ar atmosphere together with Mg pellets. The tube was put into a furnace at temperature 670 °C – 850 °C and kept for 30 min, then cooled rapidly to 27 °C. The thickness of MgB_2 thin film is about 400 nm. SEM images were taken to show the microstructure of the two samples of films (see Fig.2). Superconducting transition temperatures of them were obtained by magnetization measurement (see Fig.3).

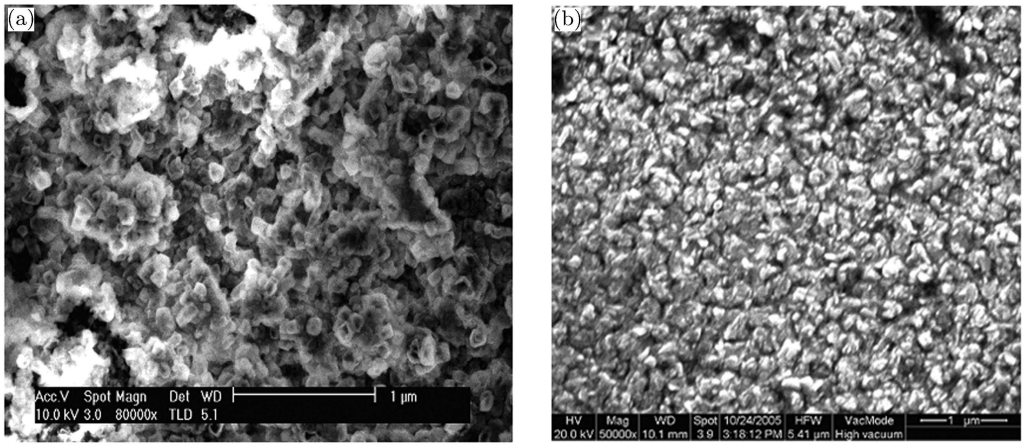


Fig.2. SEM images of the superconducting MgB_2/Al_2O_3 films. (a) Sample 1#; (b) Sample 2#.

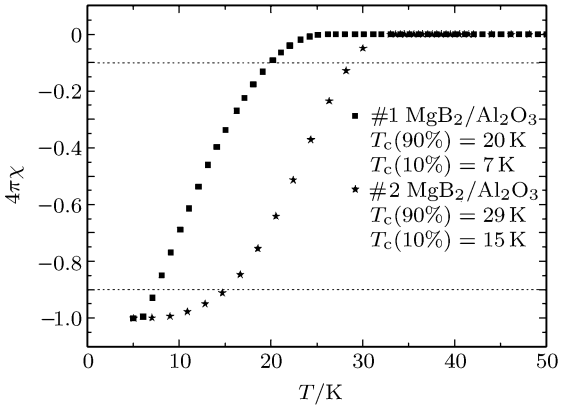


Fig.3. Temperature dependence of zero-field-cooled magnetization data at 10Oe for samples #1 and #2.

Coplanar resonators were designed using Sonnet software and fabricated by standard lithography and ion milling technique on the single-sided MgB_2/Al_2O_3 films with the dimensions of $10 \times 10 \times 0.5$ mm. The width of the central strip line is 200 μm and the spacing to each ground is 180 μm. The central strip line length of the resonator is 6 mm, the gap between central strip and port lines is 0.5 mm. Microwave properties of the coplanar resonators were measured by Agilent 8510c Vector Network Analyser at low temperature maintained by a G–M refrigerator (CSW-71). The temperature dependence of the unloaded quality factor Q_u and the resonant frequency $f_0(T)$ for the two coplanar resonators are shown in Figs.4 and 5, respectively.

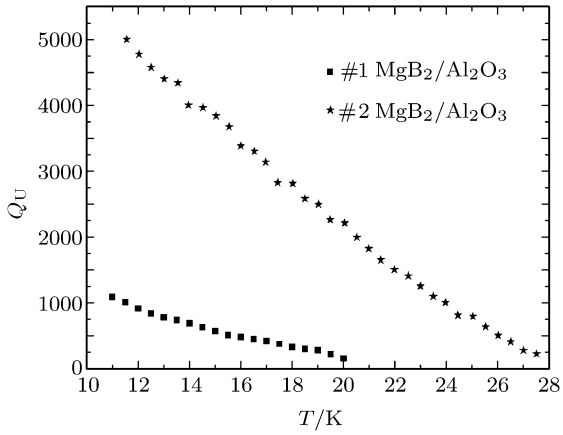


Fig.4. Temperature dependence of unloaded quality factor of resonators at fundamental mode (10 GHz) with input power $P_{input} = 0$ dBm.

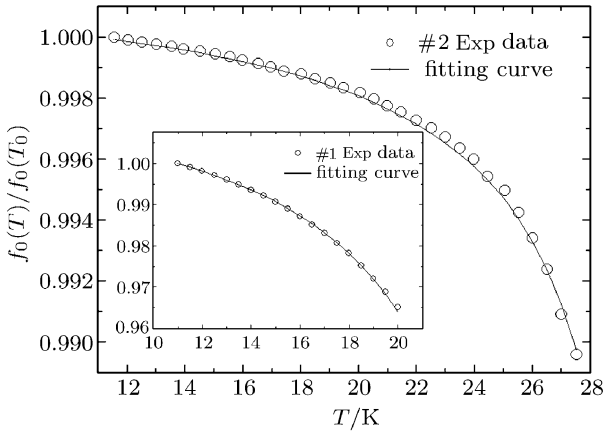


Fig.5. Temperature dependence of resonant frequency normalized to its value at the lowest temperature for sample #2. The inset shows experimental data of sample #1.

4. Results and discussions

It can be seen from Fig.2 that sample #1 has small grain sizes of about 100 nm, whereas sample #2 has larger grain sizes typically about 200 nm. It can be also seen from Fig.2 that the surface of sample #2 is more smooth than that of sample #1. Figure 3 shows the temperature dependence of the zero-field-cooled magnetization data at 10Oe for both films. A broad superconducting transition can be observed for the two thin films. The difference in superconducting transition temperature is attributed to different growth technique of the films.

As seen from Fig.4, sample #2 has higher unloaded quality factor than that of sample #1, which indicates that the former has less loss in microwave field. We take λ_{g0} as 107 nm, which is about equal to the penetration depth of high quality MgB_2 thin films given in the literature.[21−27] Parameter n is related with the quality of films, $n = 1.5$ for sample #1 and $n = 1$ for sample #2 and the penetration depth of the grain boundaries λ_{J0} of the two samples can be obtained by fitting the measured temperature dependence of resonant frequency of coplanar resonator to equation (1)–(8) (see Fig.5). For sample #1, $\lambda_{J0} = 730$ nm, thus $\lambda_{J0} \gg \lambda_{g0}$. Therefore the microwave properties of sample #1 are dominated by properties of grain boundaries. It can be attributed to the fact that grain boundaries of the film contain a certain amount of impurities and disorders which lower the superconductor transition temperature and enhance the penetration depth.[28−30] For sample #2, $\lambda_{J0} = 132$ nm, thus the penetration depth of grains is comparable to that of grain boundaries, the microwave properties of the film are dominated by both grains and grain boundaries.

The microwave surface resistance of both samples superconducting films can also be obtained. As shown in Fig.6, sample #2 has lower surface resistance than that of #1. For sample #1 with small grain sizes, the influence of grain boundaries is large compared to that of the grains and the characteristics of the film are dominated by grain boundaries, leading to a larger surface resistance. R_s is 2850 $\mu\Omega$ for sample #1 at 11 K. For sample #2, the grain sizes are larger than that of sample #1. The effect of grain boundaries is reduced, the surface resistance of sample #2 is dominated by both grain boundaries and grains, resulting in a surface resistance of $R_s = 422\,\mu\Omega$ at 11 K. Table 1 shows some published experimental data in literature.[25,30,31] It can be seen that surface resistances of our samples are larger than those of high-quality MgB_2 films. It may come from impurities and disorder of grain boundaries. As noticed in literature,[32,33] if MgO and BO_x are present in the grain boundaries as insulating components, they will have effect of separating the MgB_2 grains from each other. Klie *et al*[34] studied STEM of samples of MgB_2 and revealed details of the grain boundary structure in which two types of boundaries can be seen. The first type of boundaries is trilayers of BO_x/MgO/BO_x, where the amorphous BO_x layers, about 2 nm, sandwiches layers of MgO which is about 10 nm thick. This type of grain boundaries will be insulating. The second type of boundaries is BO_x, which is about 1 to 3 nm thick. If all the grains in the film are separated by such junctions, surface resistance of the film will increase. This is likely the case of our thin films. But MgB_2 with clear grain boundaries can have high critical density and less surface resistance due to its metal boundaries and longer coherence length. In order to reduce microwave surface resistance of the films, growth technique of MgB_2 superconducting thin films needs still be researched.

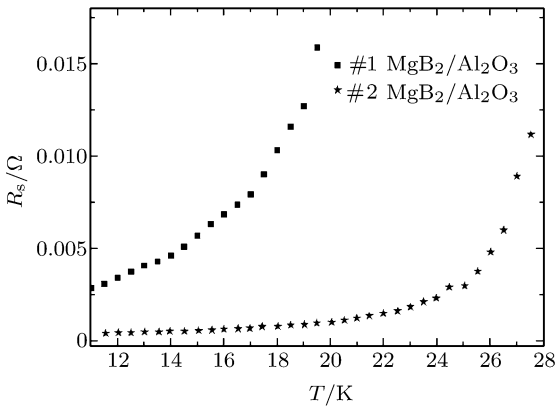


Fig.6. Surface resistance versus temperature measured at 10 GHz for samples #1 and #2.

Table 1. Surface resistance of MgB_2/Al_2O_3 (scaled to 10 GHz, according to $R_s \propto f_0^2$).

MgB_2/Al_2O_3	Resonator type	$R_s/\mu\Omega$	T/K
sample #1	coplanar	2850	11
sample #2	coplanar	422	11
Ref.[25]	dielectric	26	4.2
Ref.[30]	dielectric	4700	10
Ref.[31]	dielectric	30	10

5. Conclusion

In the paper, a grain size model is used to analyze microwave penetration depth and surface resistance of two samples of superconducting MgB_2/Al_2O_3 thin films. For sample #1 with small grain size, the microwave properties are dominated by grain boundaries, which makes sample #1 to have larger penetration depth and higher surface resistance than those of sample #2. Impurity and disorder of grain boundaries of the films affect penetration depth and surface resistance.

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