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Influence of magnetic impurities on the microwave resistance of overdoped $YBa_2Cu_3O_{7-\delta}$ films

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The temperature dependence of the microwave surface resistance for overdoped $YBa_2Cu_3O_{7-\delta}$ films has been investigated experimentally. It was shown that the observed unusual behavior of the surface resistance can be described in the framework of the spin-flip scattering of carriers, leading to the pair breaking and the subsequent recovery of superconductivity caused by the ordering trend of the magnetic impurities at low temperature. A simple phenomenological model based on the common BCS approach is suggested, which is able to interpret nicely the experimental data.

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I. INTRODUCTION

Superconducting microwave devices based on high-T_c superconductor (HTSC) thin films have a large potential market in the area of microwave communications. However, surface impedance measurements of superconducting cuprates in the microwave range exhibit an unexpectedly high loss and a strong field dependence even at low current levels. The understanding and minimization of the microwave losses are important for many passive-device applications such as bandpass filters and delay lines for communication systems and antennas for NMR tomography.

Three theoretical approaches have been used for existing explanations of the unusual temperature behavior of the surface impedance in HTSC compounds. The first of them suggests the existence of weak links such as grain or twin boundaries in the HTSC materials.[1–3] The second one is based on the semimicroscopic *d*-wave model.[4,5] The third takes into account a variety of electron scattering mechanisms.[6,7]

However, there is a lot of experimental evidence that the physical properties are very sensitive to oxygen concentration in these compounds.[8] For example, a deficit of oxygen ($\delta \leqslant 0.5$) in $YBa_2Cu_3O_{7-\delta}$ results in the formation of the so-called 60-K phase.[9] In Ref. 10 it was shown that, in an overdoped $YBa_2Cu_3O_{7-\delta}$ at $\delta < 0.05$, two superconducting phases can exist with a difference in critical temperature of 2.5 K. According to these results, there is the optimal oxygen content of $\delta = 0.08$ for the $YBa_2Cu_3O_{7-\delta}$ compound. Overdoping or underdoping of oxygen can lead to specific changes in the electron properties of the compound caused by a charge transfer. The physical nature of this phenomenon is quite far from a complete understanding because of the very complicated electron structure in such materials. It has been shown that, under the assumption of a special type of oxygen ordering in Cu-O chains,[11] it is possible to explain this phenomenon. On the other hand, the doping of oxygen is accompanied by a change in value and sign of the charge at the oxygen sites, which must result in the formation of noncompensated local magnetic moments.[12] In fact, their presence has been established by several independent experiments: the unusual behavior of the heat capacity (Schottky anomalies),[13] the muon-spin-resonance data,[14,15] the positive curvature of the upper critical magnetic field $H_{c2}(T)$,[16–18] and so on. The recently predicted effect of a phase separation[19–21] can also induce the formation of small spin-polarized clusters in the considered compounds. Thus, the HTSC cuprates can be treated as intrinsically inhomogeneous materials that always contain magnetic impurities, which decreases the critical temperature. According to a theoretical estimation, the intrinsic T_c (in the absence of magnetic impurities) must be 160–170 K for all cuprates including $YBa_2Cu_3O_{7-\delta}$.[20] It is absolutely reasonable to suggest that such significant alterations in the electron subsystem caused by the changed oxygen concentration must be manifested in the microwave properties of the HTSC compounds. It is worth noting that in the overdoped $YBa_2Cu_3O_{7-\delta}$ a part of the paramagnetic oxygen ions can be in the unbound state and also play the role of the magnetic impurities.

Taking into account the above results and assumptions, we carried out microwave investigations on overdoped $YBa_2Cu_3O_{7-\delta}$ thin films prepared by the dc magnetron sputtering method.

II. EXPERIMENT AND CHARACTERISTICS OF THE SAMPLES

Contrary to the conventional sputtering methods overdoped $YBa_2Cu_3O_{7-\delta}$ thin films were deposited in a pure oxygen atmosphere instead of a gas mixture. The cathode voltage was 300–350 V, and the current in the plasma was ~20 mA. The distance between target and substrate was 8–10 mm. The substrate temperature during the film deposition was 720–750 °C. $SrTiO_3$ single crystals were used as substrates with the (100) working surface.

The content of oxygen in the prepared films was estimated from analysis of the θ-2θ x-ray diffraction (XRD) patterns. As was shown in Ref. 10 the out-of-plane lattice parameter c of $YBa_2Cu_3O_{7-\delta}$ depends linearly on the oxy-

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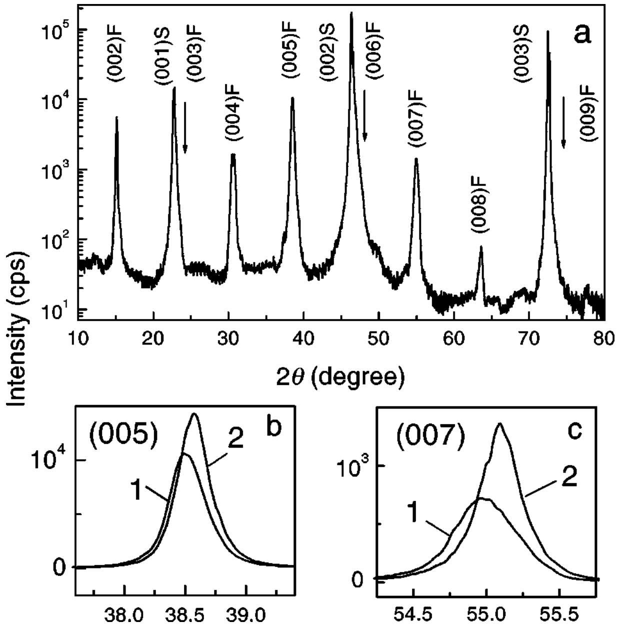

FIG. 1. θ-2θ XRD patterns of $YBa_2Cu_3O_{7-\delta}$ thin films. (a) θ-2θ XRD scan for the overdoped film. S and F denote substrate and film, respectively. (b) The (005) and (c) the (007) diffraction peaks of the optimally doped (1) and overdoped (2) films.

gen concentration in a range of $\delta \simeq 0$–0.2 and this relation can be described by a simple empirical formula c (nm) $\simeq 1.168$ (nm) $+0.0144\delta$ (nm).

Figure 1(a) presents a θ-2θ XRD scan for film deposited in a pure oxygen atmosphere, which was obtained using a Rigaku diffractometer with Cu $K\alpha$ radiation. Only the $(00l)$ peaks of the substrate and film are significantly manifested, indicating that the deposition results in a highly oriented film. The lattice parameters evaluated directly from the XRD data were plotted against $\cos^2\theta/\sin\theta$. By extrapolating a fitted straigth line to $\cos^2\theta/\sin\theta=0$, a more precise determination of the lattice parameter is possible.[22] Figures 1(b) and 1(c) display the peak positions for the (005) and (007) reflections, respectively. Curves 1 belong to $YBa_2Cu_3O_{7-\delta}$ thin film prepared on a similar $SrTiO_3$ substrate by a laser ablation method[23] and curves 2 are for the overdoped film in the present study, deposited by dc sputtering in the pure oxygen atmosphere. The different peak positions for both films are evidence for the different oxygen contents. An estimation of the lattice parameters using the aforementioned extrapolation method shows that $c \simeq 1.1694$ nm for the laser-deposited film and $c \simeq 1.1682$ nm for the sputter-deposited one. It is worth noting that the other films, prepared by dc sputtering in a pure oxygen atmosphere, also have similar values for the lattice parameter of $c \simeq 1.1680$–1.1683 nm. The empirical formula for the dependence of the lattice parameter c on the oxygen content leads us to estimate the values for δ of the investigated films. δ turns out to be about 0.1 and 0–0.02 for the laser- and sputter-deposited films, respectively. Therefore, the former can be treated as optimally oxygen doped and the latter as oxygen overdoped, according to the phase diagram for the $YBa_2Cu_3O_{7-\delta}$ compound.[10]

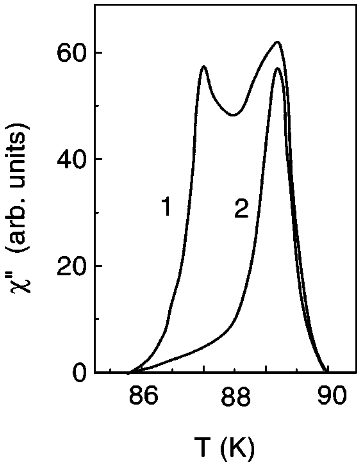

FIG. 2. Temperature dependence of the ac magnetic susceptibility for overdoped (1) and optimally doped (2) $YBa_2Cu_3O_{7-\delta}$ thin films.

On the other hand, in the overdoped $YBa_2Cu_3O_{7-\delta}$ compound, two superconducting phases can exist with different critical temperatures.[10] Owing to the so-called ''shunt effect'' the two-phase superconducting state is not revealed by the conventional dc potentiometric measurements. The onset of the critical temperature for the prepared films, measured by the four-point-probe method, was around 90 K with $\Delta T_c \simeq 1.5$–2.5 K. However, the temperature behavior of the out-of-phase component of the ac magnetic susceptibility (χ'') was significantly different between the overdoped and the optimally doped $YBa_2Cu_3O_{7-\delta}$ films. The ac magnetic susceptibility experiments were performed with a compensated mutual-inductance bridge. Figure 2 displays the tempetature-dependent $\chi''(T)$ near the superconducting transition for the overdoped (curve 1) and the optimally doped (curve 2) films, measured at an amplitude of the ac magnetic field of 10 mOe and a working frequency of 1 kHz. It is seen that the optimally doped film manifests one peak while two peaks are observed for the overdoped film. The results obtained coincide with the inductive data mentioned in Ref. 10 for $YBa_2Cu_3O_{7-\delta}$ single crystals. It is well known that the two-peak behavior of the dissipative part of the ac magnetic susceptibility is direct evidence for an inhomogeneity in the superconducting order paramereter and for the existence of the two superconducting phases in the HTSC compounds.[24–26] Consequently, even though the potentiometric measurements indicated only one superconductiong transition for the overdoped $YBa_2Cu_3O_{7-\delta}$ film, the film can be really treated as a two-phase superconducting system.

The residual resistivity at room temperature (ρ_{300}), measured by the dc four-point-probe method, was 200–300 $\mu\Omega$ cm (for the best samples), and came to be $\simeq 500$ $\mu\Omega$ cm after five to seven depositions using a target. This effect is connected with the surface degradation and the stoichiometry perturbation of the target during the repeated plasma actions. A regrinding of the degraded surface leads, as a rule, to the recovery of the performance characteristics of the target and of the preparation of films with low residual resistivity at room temperature. The residual resistivity of the the optimally doped $YBa_2Cu_3O_{7-\delta}$ film, prepared by laser

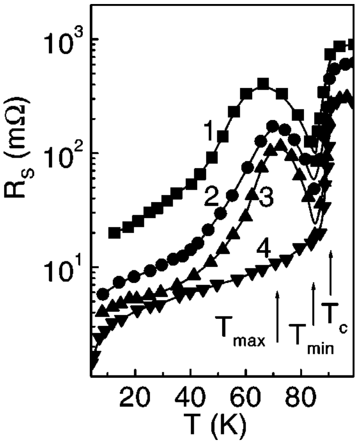

FIG. 3. Temperature dependence of the microwave surface resistance for overdoped $YBa_2Cu_3O_{7-\delta}$ thin films with different ρ_{300}: (1) 450 $\mu\Omega$ cm, (2) 320 $\mu\Omega$ cm, (3) 250 $\mu\Omega$ cm. (4) An experimental curve for the optimally doped thin film.

ablation, was $\simeq 180$ $\mu\Omega$ cm.

The final thickness of all the investigated films was between 100 and 120 nm. The measurements of the surface resistance (R_s) were carried out in a specially designed copper cavity at a frequency of 32.4 GHz by replacing the end-plates of the films in a H_{011} mode. An extensive description of the experiment has been given elsewhere.[27]

III. RESULTS AND DISCUSSION

The experimental results show that the $R_s(T)$ curves for the overdoped films have a nonmonotonic behavior with a sharp minimum at $T_{\min} \leqslant T_c$ and a broad maximum at a lower temperature ($T_{\max} \approx 60$–70 K) as shown in Fig. 3. Such type of behavior of $R_s(T)$ has a principal distinction from that observed for the optimally doped film. It is seen that R_s decreases monotonically down to the lowest temperature and no abrupt peculiarity in the form of minimum or maximum (curve 4).

Several authors[1,2] attribute the wide maximum of the $R_s(T)$ curves to a microstructure inhomogeneity of the objects and to the existence of weak links where superconductivity could be partly or completely suppressed. The weak links act as Josephson junctions of the weakened superconductivity, and the temperature dependence of the surface resistance is governed by the critical Josephson current and the leakage current.[2] The grain or twin boundaries are usually considered as the weak links. However, the maximum on the $R_s(T)$ curves is observed for the $YBa_2Cu_3O_{7-\delta}$ single crystals as well as for the films, prepared by various methods and obviously having different imperfections.[28] Second, it was reported[2] that the $YBa_2Cu_3O_{7-\delta}$ film prepared by magnetron sputtering shows the maximum of $R_s(T)$ only after an aging at room temperature in air for 2 weeks. It is, however, hard to imagine that such a low-temperature treatment could lead to significant changes in microstructure.

Another attempt to explain the $R_s(T)$ upturn by using d-wave symmetry of the order parameter[4,5] also seems to fail for the same reasons. The difference in sample preparation hardly results in changes of the symmetry of the order parameter, since it does not influence drastically on the intrinsic electron structure of the compound. Moreover, the analysis of the temperature dependence of the surface resistance, performed for the $YBa_2Cu_3O_{7-\delta}$ single crystal in the framework of the d-wave model,[29] was not consistent with the experimental data.

On the other hand, a combination of the elastic and inelastic electron scattering plays an important role in increasing the microwave resistance.[7,30] Reference 7 shows a computer simulation of the $R_s(T)$ dependence for the $YBa_2Cu_3O_{7-\delta}$ compound, taking into account the electron scattering rate which consists of a temperature-independent term and a Grüneisen-like term for the inelastic scattering. Even though this approach turns out to describe well the nonmonotonic behavior of $R_s(T)$, the predicted location of the maximum and shape of the minimum contradict our experimental results. Moreover, it is not clear what is the reason for a huge rise in the number of the normal electrons in the superconducting state at low temperatures.

It was shown that, in the underdoped $YBa_2Cu_3O_{7-\delta}$ compound, the surface resistance R_s is not equal to the surface reactance X_s.[31] This indicates that the pseudogap state above T_c is not a normal metal with ordinary Ohmic conductivity, and signifies the importance of magnetic contributions to the microwave impedance.

Taking into account all that mentioned above, we suggest the following explanation of the unusual behavior of $R_s(T)$.

(1) Two superconducting energy gaps coexist in the HTSC compound, e.g., for the Cu-O planes and the Cu-O chains. As noticed above, the overdoped $YBa_2Cu_3O_{7-\delta}$ compound can contain two separated superconducting phases[10] which belong to planes and chains. Owing to a large increase of the coherence length, the wave function of superconducting electrons overlaps between adjacent planes and chains near T_c, and both gaps transform into one, which determines the critical temperature of the compound. It is considered that, in this state, the magnetic impurity concentration is less than a critical value[32] and the total suppression of superconductivity is manifested only by a total decrease in T_c, with respect to an intrinsic theoretical value declared in Ref. 20. With decreasing temperature the wave function overlap is decreased (the proximity effect is reduced) and the gaps can be treated as separate.

(2) At a high temperature (near T_c) the magnetic impurities can be treated as independent centers which cause a spin-flip scattering of carriers.[20] The spin-flip scattering of superconducting electrons leads to the pair-breaking effect and the collapse of the weaker energy gap of the Cu-O chains.[32–34] As the temperature decreases, the interaction between impurities (the ordering trend) becomes important. Such correlation processes frustrate the spin-flip scattering and, thereby, the pair-breaking effect, because it becomes impossible to satisfy the spin-conservation law. As a result, the superconducting state becomes less depressed, which leads to the recovery of superconductivity.[20] It is worth noting that the magnetic recovery effect, connected with a decrease in the microwave absorption for a small dc magnetic field, has been already observed.[35]

Let us consider only the real part of the microwave impedance. $R_s(T)$ can be described by the well-known expression[6]

$$\frac{R_s(T)}{R_s(T_c)}=\sqrt{\frac{\sigma(T_c)(\varepsilon^{1/2}-1)}{\sigma_2\varepsilon}}, \tag{1}$$

where $\sigma(T_c)$ is the conductivity at T_c, $\varepsilon=1+(\sigma_1/\sigma_2)^2$, and σ_1 and σ_2 are the real and imaginary parts of the complex conductivity, respectively. Based on the BCS model for σ_1 and σ_2, one can write the simple expressions[36]

$$\frac{\sigma_1(T)}{\sigma(T_c)}\simeq\frac{\Delta(T)}{2k_BT}\cosh^{-2}\left(\frac{\Delta}{2k_BT}\right)\ln\left(\frac{\Delta}{\hbar\omega}\right),$$

$$\frac{\sigma_2(T)}{\sigma(T_c)}=\frac{\pi\Delta(T)}{\hbar\omega}\tanh\left(\frac{\Delta}{2k_BT}\right). \tag{2}$$

Here, Δ is the superconducting energy gap, ω is the microwave frequency, and k_B is Boltzmann's constant. The value of the conductivity at the critical temperature can be estimated from the experimental magnitude of R_s at $T=T_c$ by using $R_s(T_c)=[\omega\mu_0/2\sigma(T_c)]^{1/2}$, where μ_0 is the magnetic constant.

As a rule, the energy gap is a product of the temperature-independent term Δ_0 (energy gap at zero temperature) and a function $F(T)$ whose behavior changes from an exponential law at $T<T_c/2$ to a power law near T_c.[37] However, the spin-flip scattering of superconducting electrons, accompanied by the pair-breaking effect, leads to a suppression of Δ_0, and this term becomes temperature dependent as well.

The presence of magnetic impurities invokes a decrease of T_c with respect to the intrinsic value T_{c0} in the absence of magnetic impurities, because of the pair-breaking effect.[32–34] Such a depression is described by the well-known equation[32]

$$-\ln\left(\frac{T_c}{T_{c0}}\right)=\psi\left(\gamma_s+\frac{1}{2}\right)-\psi\left(\frac{1}{2}\right). \tag{3}$$

Here, ψ is the digamma function, and $\gamma_s=\Gamma_s/2\pi T_c$, where $\Gamma_s=\tau_s^{-1}=\Gamma_0 N(0)n_m$ is the spin-flip scattering amplitude. Γ_0 is a constant and n_m is the concentration of magnetic impurities, and for the electronic density of states $N(0)\sim n_e^{1/3}$ where n_e is the concentration of superconducting electrons. At almost all temperatures this parameter Γ_s can be treated as temperature independent if the interaction between magnetic impurities is absent (the small ''Kondo'' term is neglected as a rule).[32] However, owing to the impurity ordering trend the number of independent magnetic impurities (which result in spin-flip scattering) is reduced in the low-temperature range. This is why the spin-flip scattering amplitude becomes temperature dependent, $\Gamma_s(T)=\Gamma_0 f_s(T)$. Here, Γ_0 is the spin-flip scattering amplitude when all the magnetic impurities are independent, and $f_s(T)=n_e^{1/3}n_m$ is a function which describes the temperature dependence of the *effective* number of the independent magnetic impurities. It is necessary to emphasize that the *effective* number of magnetic impurities, which participate in spin-flip scattering, depends on not only the concentration of magnetic impurities, but also on the electron concentration.[32,38]

Therefore, the expression for the temperature dependence of the total superconducting energy gap Δ can be written in the next simple form

$$\Delta(T)=2.1k_BT_{c0}\left[1-\frac{\pi}{4}\frac{\Gamma_0 f_s(T)}{k_BT_{c0}}\right]F(T), \tag{4}$$

where $F(T)$ represents a function for the BCS-like behavior of the energy gap as mentioned above. In constructing Eq. (4) we used a relation, $\Delta_0=2.1k_BT_{c0}$, which is very often obtained experimentally.[1,2]

From Eq. (4) it follows that the value of the energy gap vanishes in both cases, i.e., when $F(T)\rightarrow 0$ above the critical temperature and when the term in square brackets becomes zero due to the spin-flip scattering, and then the pair-breaking effect results in a normal state. For the latter case we can estimate the maximum scattering rate $\Gamma_0\simeq 1.27T_{c0}$. Of course, the real value is smaller because only part of the sample is transformed into the gapless state.

The exact evolution of $f_s(T)$ is an interesting problem in the microscopic theory, and some aspects of this problem were addressed elsewhere.[21,32,38] However, the main subject of this paper is the behavior of the surface microwave resistance, and we restrict ourselves to a phenomenological approach. Based on common considerations for magnetic transitions we can assume that the number of noncorrelated magnetic impurities, n_m, decreases with decreasing temperature, becoming zero (or a small value) at low temperatures. The temperature behavior of the order parameter for any magnetic system in a temperature range below the critical temperature ($T<T_M$) can be described in the following form (in the framework of the mean-field approximation):[39]

$$\eta=\tanh\left(\frac{zJ}{k_BT}\eta\right), \tag{5}$$

where J is the exchange integral for magnetic interaction, z is the coordination number for crystal lattice, and $zJ\simeq k_BT_M$. Consequently, the temperature behavior of the normalized concentration for the noncorrelated magnetic impurities will be equal to $n_m=1-\eta$.

In addition, at a temperature very near T_c, the function $f_s(T)$ must be also zero, due to an overlapping of the superconducting electrons between adjacent planes and chains, and the resultant state has a concentration of magnetic impurities smaller than a critical value.[20,32,38] This statement reflects the fact that the spin-flip scattering of superconducting electrons leads to the pair-breaking effect only after space separation of the plane and chain energy gaps and when the concentration of magnetic impurities becomes higher than a critical value with respect to the number of superconducting electrons that belong to the Cu-O chains. It is reasonable to suggest that the temperature of the superconducting transition along the Cu-O chains is shifted below the critical temperature of the whole sample. The last assumption is supported by the occurrence of the second peak on the temperature dependence of magnetic susceptibility (see curve 1 in Fig. 2), which can serve as a evidence for the

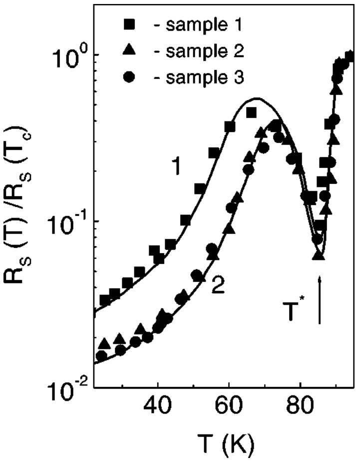

FIG. 4. Temperature dependence of the normalized surface resistance $R_s/R_s(T_c)$ for the overdoped samples in Fig. 3. The solid line is the theoretical curve obtained from Eq. (1) using the following fitting parameters for f_s: $T_1=87$ K, $T_M=70$ K, $T_{c0}=90$ K, $\Gamma_0=0.89T_c$, and the normalized residual surface resistance $R_s(0)/R_s(T_c)=0.015$ for curve 1, and $T_1=87$ K, $T_M=75$ K, $T_{c0}=90$ K, $\Gamma_0=0.89T_c$, and $R_s(0)/R_s(T_c)=0.01$ for curve 2.

existence of two superconducting phases in overdoped $YBa_2Cu_3O_{7-\delta}$ films. By designating the critical temperature of the second (low-temperature) phase as T_1, the temperature dependence of the concentration of the superconducting electrons that belong to the Cu-O chains could be expressed by $n_e\sim(T_1-T)/T_1$.[37] Consequently, the temperature dependence of f_s in the entire range can be represented by $f_s(T)=[(T_1-T)/T_1]^{1/3}(1-\eta)$. On the other hand, it must be emphasized that the magnetic transition in HTSC compounds has a more fundamental nature connected with the quantum phase transitions in cuprates.[19–21]

Figure 4 shows the experimental temperature dependence of the normalized surface resistance for two overdoped $YBa_2Cu_3O_{7-\delta}$ films (with lower resirual resistances) in Fig. 3, together with the theoretical one. The solid line is the theoretical curve calculated using a set of equations (1), (2), and (4). The following fitting parameters were employed for the calculation: $T_1=87$ K, $T_M=75$ K, $T_{c0}=90$ K, $\Gamma_0=0.89T_{c0}$, and $R_s(0)/R_s(T_{c0})=0.01$ for samples 2 and 3 (curve 2) and $T_1=87$ K, $T_M=70$ K, $T_{c0}=90$ K, $\Gamma_0=0.89T_{c0}$, and $R_s(0)/R_s(T_{c0})=0.015$ for sample 1 (curve 1). Here, $R_s(0)/R_s(T_{c0})$ is the normalized residual surface resistance which was used as an additional term in Eq. (1). It is seen that the theoretical curve displays good agreement with the experimental data.

The physical meaning and reality of the magnitudes of the fitting parameters can be discussed in a more detail. T_{c0} corresponds to the onset critical temperature of the superconducting transition for the films. The estimated value of the amplitude of the scattering rate Γ_0 at the critical temperature is very close to that for $YBa_2Cu_3O_{7-\delta}$ single crystals ($\Gamma_0\simeq0.8T_c$).[40,41] T_1, which coincides with $T_{\min}$ of the experimental $R_s(T)$ curves (see Fig. 3), can be treated as the temperature of the space separation of the energy gaps between Cu-O planes and chains or as the temperature for the appearance of the second (low-temperature) energy gap. According to Ref. 10 and an analysis of the $\chi''(T)$ curve, T_1 must be about 87.5 K, while our fitting shows $T_1\approx87$ K. It is not a very large difference when the phenomenological character of the chosen $f_s(T)$ function is taken into account. T_M in our model plays the role of the temperature which describes the onset of the magnetic ordering.

In this paper we have not considered in detail the physical nature of the residual surface resistance at low temperatures ($T\leqslant0.5T_c$), but instead have introduced this as an additional term in Eq. (1). This problem has been already solved in a few publications in the framework of the two-fluid model (see Refs. 6 and 7 for the review). If it is assumed that the effects of the crystalline disorder or nonmagnetic impurities can be manifested in the spin-flip pair-breaking rate as the magnetic impurities,[42] then the expression of Γ_s for Eq. (3) must be modified to $\Gamma=\Gamma_s+\Gamma_{in}+\Gamma_{el}$. Here, Γ_{in} and Γ_{el} are the inelastic and elastic scattering rates, respectively. An incoherent combination of the elastic and inelastic scattering rates was suggested by Bonn *et al.*[30] A computer simulation in the framework of the Grüneisen-like approximation for the scattering rates (Γ_{in} and Γ_{el}) allows us to describe the low-temperature behavior of the surface resistance in the HTSC compounds.[7] Unfortunately, the large number of the fitting parameters in this case makes the interpretation of their physical meaning very difficult. On the other hand, due to the small thickness (below the penetration depth) of the investigated films and a power transmission into the substrate, the total residual resistance must contain an additional contribution.[43]

Since the dc sputtering process leads to a dielectrization of the target, the deposition rate can be decreased after the repeated plasma actions. Therefore, the thickness of a film deposited later (sample 1) could be smaller than that of a film prepared earlier (sample 3). That is why some fitting parameters [T_M and $R_s(0)/R_s(T_{c0})$] for this film are different from those for samples 2 and 3. Therefore, it is concluded in our case that the value of the surface residual resistance is governed by substrate effects rather than by elastic and inelastic scattering.

IV. SUMMARY

The main results of this paper can be summarized as follows.

(1) An unusual temperature behavior of the microwave surface resistance was observed in overdoped $YBa_2Cu_3O_{7-\delta}$ thin films. The experimental results show that the $R_s(T)$ curves have a nonmonotonic behavior with a sharp minimum at $T_{\min}\leqslant T_c$ and a broad maximum at a lower temperature ($T_{\max}\approx60$–70 K). The optimum-doped $YBa_2Cu_3O_{7-\delta}$ thin film does not display such a type of anomaly.

(2) It was found that the observed anomalous temperature behavior of the microwave surface resistance in $YBa_2Cu_3O_{7-\delta}$ thin films turns out to be determined by the oxygen content or ordering rather than by microstructure imperfections or the *d*-wave symmetry of the superconducting

order parameter. The variation of the oxygen contents can result in a considerable relocation of the charge and a rise in the concentration of the magnetic impurities in the compound.

(3) By considering that the state of magnetic impurities is dependent on temperature, we suggest a simple phenomenological model, in the framework of the common BCS approach, describing successfully the experimental data of the unusual $R_s(T)$ behavior in the overdoped $YBa_2Cu_3O_{7-\delta}$ films.

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