3RD HARMONIC AC SUSCEPTIBILITY IN OXIDE SUPERCONDUCTORS

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ABSTRACT

In order to investigate the effect of reversible motion of fluxoids, the 3rd harmonic of complex AC susceptibility was measured for Y-based superconducting powder and QMG-processed bulk specimens. The critical current density was estimated from the experimental results using the theoretical model of Campbell for the reversible motion of fluxoids and compared with the estimation from DC magnetization. Deviation from the estimated value from DC magnetization is remarkable when the applied AC magnetic field is small. It is considered that the reversible fluxoid motion at low AC magnetic fields is much more prominent than expected in the present theory.

KEYWORDS: third harmonic AC susceptibility, reversible fluxoid motion, Campbell's model critical current density

INTRODUCTION

The third harmonic AC susceptibility (χ_3', χ_3'') has been used for characterization of oxide superconductors, since it is possible to eliminate the noise with the fundamental frequency and the effect of viscous force against the fluxoid motion, and more correct information of the pinning effect is expected to be obtained[1]. On the other hand, it has been found that magnetic behaviors such as the slope of DC magnetization and the fundamental and harmonic AC susceptibilities deviate from the prediction of completely irreversible Bean's critical state model, when the fluxoid motion becomes reversible[2]. The reversible fluxoid motion is significant when the effective size of the superconductor, d, is comparable to or smaller than Campbell's AC penetration depth, λ_0'. Here, the effective size is given by the smaller value of radiuses of the loop of superconducting shielding current.

The numerical calculation of χ_3' and χ_3'' was carried out based on Campbell's model in which the reversible fluxoid motion was taken into account and compared with the experimental result on superconducting Rb_3C_{60} powder[2]. The peak values of χ_3' and χ_3'' were remarkably smaller than the predicted values of Bean's model, when the reversible fluxoid motion was prominent. The decrease in the peak values of χ_3' and χ_3'' was observed according to increasing DC magnetic field and/or temperature. These results could be explained from the magnetic field and temperature dependence of the critical current density, J_c and Campbell's AC penetration depth, λ_0'. That is, J_c reduced and λ_0' became large in higher magnetic field and/or high temperature, resulting in the more prominent reversible fluxoid motion. However, in spite of the theoretical prediction that the absolute value of negative peak in low AC magnetic field was larger than the value of positive peak in high AC magnetic field, the negative peak value was smaller. It was speculated that the motion of fluxoids changed more quickly from reversible to irreversible than the theoretical prediction in large AC magnetic field. A further discussion is necessary for explanation of the AC magnetic field dependence of χ_3''.

It is expected that the reversible fluxoid motion in oxide superconductor is significant at high temperatures as well as Rb_3C_{60} powder, since the superconducting specimen is frequently divided by cracks and weak links and the effective size of superconductor is considered to be small. In this paper, the effect of reversible fluxoid motion on the third harmonic AC susceptibility is measured in Y-based powder and bulk specimen prepared by the QMG process. The results is analyzed using the numerically calculated result based on Campbell's model and compared with the experimental

result of DC magnetization. Discussion is given for the estimation of critical current density from the third harmonic AC susceptibility.

EXPERIMENTS

The specimens investigated were Y-based powder and bulk prepared by the QMG (Quench and Melt Growth) process. A sintered Y-Ba-Cu-O was powdered and mixed with an insulating powder of Y_2O_3 with the ratio of 1:2. The mixed powder was pressed with the pressure of about 1 t/cm^2 and fixed in epoxy resin. In this powder specimen, the shielding current induced by the external AC field was limited inside the superconducting powders. The effective size of the superconductor, d, is expected to be equal to the size of powder and is in the range of $d = 1 \sim 10$ μm. The QMG specimen was cut into a slab shape with the size of $4.55 \times 3.20 \times 0.85$ mm^3 and the c-axis was oriented perpendicular to the wide surface. In the case of QMG specimen, shielding current can not flow uniformly in the specimen because of disturbance by defects such as cracks. Therefore, d is expected to be given by the space of cracks along the a-b plane[3]. It is to be noted that the thickness of the specimen, $D = 0.85$ mm, in the estimation of J_c from DC magnetization is used. Hence, J_c estimated from the DC magnetization is not equal to the local critical current density but is a kind of average of the local and the transport critical current densities in the QMG specimen[4]. The critical temperature measured from the imaginary part of the AC susceptibility were 90.5 K and 90.2 K for the powder and QMG specimens, respectively.

The AC magnetic field dependence of the fundamental (χ_1', χ_1'') and the third harmonic (χ_3', χ_3'') AC susceptibilities was measured at constant temperature and DC magnetic field. The DC and superposed AC magnetic field were applied along the long axis of the QMG specimen, up to 6 T and 0.03 T, respectively. The temperature was controlled in gas He atmosphere in the range of 60 K to T_c. The DC magnetization was measured by SQUID magnetometer (MPMS-7).

RESULTS AND DISCUSSION

Figure 1(a) and (b) show the AC magnetic field dependences of χ_3'' for the powder and QMG specimens in various DC magnetic fields at 81 K, and 87 K, respectively. It is found that the peak value of χ_3'' decreases monotonically with increasing DC magnetic field in the both specimens. Similar results are also observed when the temperature is increased. These results can be explained from the dependences of the critical current density on magnetic field and temperature as abovemen-

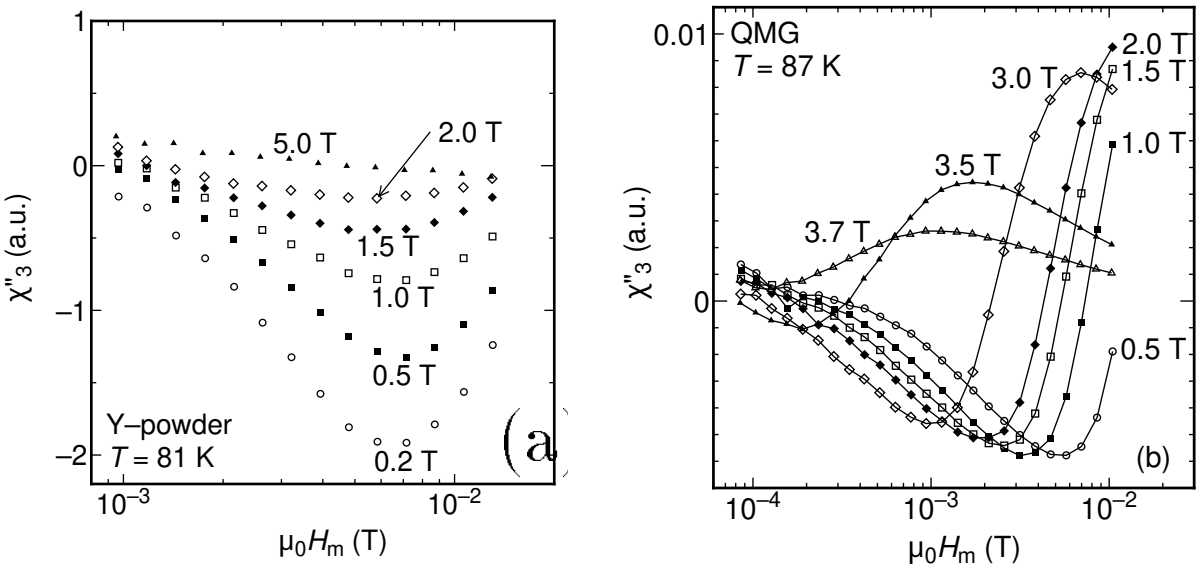

Fig. 1. AC magnetic field dependence of χ_3'' in various DC magnetic fields in (a) powder specimen at 81 K and (b) QMG specimen at 87 K.

tioned. The positive peaks are observed in Fig. 1(b) while not in Fig. 1(a). This comes from the difference in $d/2\lambda_0'$ between the two specimens, i.e., J_c and d are smaller in the powder specimen than those in the QMG specimen. It means that $d/2\lambda_0'$ is considered to be smaller in the powder specimen than in the QMG specimen. Therefore, the reversible fluxoid motion is more prominent in the powder specimen. The value of the positive peak is larger than the absolute value of the negative peak in the QMG specimen. This is similar to the observation for Rb_3C_{60}[2].

Here, the values of J_c estimated from the peaks of χ_1'', χ_3' and χ_3'' are compared with the estimation from the result of DC magnetization. The AC magnetic fields at the peaks of χ_1'', χ_3' and χ_3'' are uniquely determined by $d/2\lambda_0'$. For example, the peak field of χ_1'', H_{mp}, is given by[5]

$$H_{mp}/H_p = 3^{1/2}[1 + 2(2\lambda_0'/d)^2], \tag{1}$$

where $H_p = J_c d/2$ is the penetration field. The value of $d/2\lambda_0'$ can be estimated from the slope of the minor curve in DC magnetization, S[3]. It is known that S is determined uniquely as a function of $d/2\lambda_0'$ as[6]

$$S = 1 - \frac{2\lambda_0'}{d}\tanh\left(\frac{d}{2\lambda_0'}\right). \tag{2}$$

Therefore, $d/2\lambda_0'$ is obtained from the observed S value. Then, J_c can be estimated by H_{mp}/H_p calculated from Eq. (1) and observed H_{mp}. The value of J_c from the hysteresis of DC magnetization, ΔM, is obtained from $J_c = 2\Delta M/D$.

The results of estimated J_c from the peaks of various AC susceptibilities and DC magnetization of the powder specimen are shown in Fig. 2(a), where d is assumed as 5 μm. In this case the estimated J_c is the local critical current density and should be the same as the J_c from DC magnetization. The latter J_c obtained in the irreversible limit is considered to be close to the true value. It is found in Fig. 2(a), however, that the estimated J_c from DC magnetization is smaller than the estimations from AC susceptibilities. Thus, the J_c values obtained from the AC susceptibility is still overestimated. In addition, the values estimated from the respective peaks are different. That is, the negative value of the peak of χ_3'' leads to a largest J_c, χ_1'' leads to a medium one and χ_3' leads to a smallest one. On the other hand, the peak fields predicted by Bean's model are shown in Table 1. This order also holds even in the case of $d/2\lambda_0' = 0.1$. Therefore, it is found that the difference between the theoretical prediction and the experimental result is larger for the lower AC

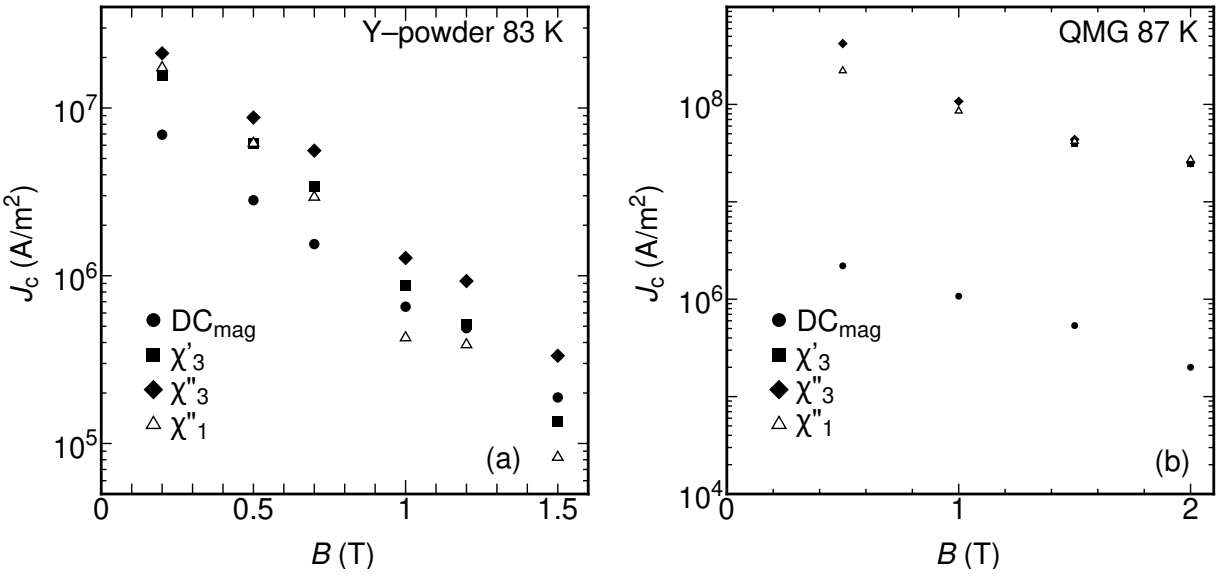

Fig. 2. Critical current density estimated from the various peaks of AC susceptibilities and DC magnetization for (a) powder specimen and (b) QMG specimen.

Table 1. The normalized amplitudes of AC magnetic fields at the peaks, $H_{\rm mp}$, of various AC susceptibilities predicted by Bean's model.

	negative peak of χ_3''	χ_1''	χ_3'	positive peak of χ_3''
$H_{\rm mp}/H_{\rm p}$	1.38	1.41	2.67	9.65

magnetic field. In general, the overestimation of $J_{\rm c}$ is caused when the irreversible Bean model is applied for the case of the significant reversible fluxoid motion. The above results insist that $J_{\rm c}$ is still overestimated even by Campbell's model in which the effect of reversible fluxoid motion is taken into account. Therefore, it is speculated that the reversible fluxoid motion at low AC magnetic fields is much more prominent than expected in the present theory.

In the QMG specimen the value of $J_{\rm c}$ estimated from DC magnetization is a kind of average of local and transport critical current densities. The value of $J_{\rm c}$ estimated from AC susceptibility is also another kind of average value. In addition, it is expected to depend on the AC magnetic field. Because of these two kinds of currents, AC magnetic field dependence of susceptibilities deviates from the present theory in which the single $J_{\rm c}$ value independent of AC magnetic field is assumed. However, we shall dare to estimate the critical current density in this specimen from AC susceptibility. We assume that the specimen is an assembly of plates with the thickness of $d = 20$ μm in each of which $J_{\rm c}$ has a single value. The results of estimated $J_{\rm c}$ are shown in Fig. 2(b). In spite of too simplified assumption, the similar result to the powder specimen is observed that $J_{\rm c}$ estimated from the peak of χ_3'' is largest. Hence, the abovementioned behavior speculated in the powder specimen is also expected to occur in the QMG specimen. It is desired to establish a new theoretical model that can explain the reversible fluxoid motion at low AC magnetic fields.

SUMMARY

In this paper, the fundamental and third harmonic AC susceptibilities of Y-based superconductors were measured and the following results are obtained. (1) The peak value of χ_3'' decreases monotonically and the reversible fluxoid motion becomes prominent at higher DC magnetic field and/or higher temperature. (2) From the comparison of $J_{\rm c}$ estimated from AC susceptibilities (χ_1', χ_3', χ_3'') and DC magnetization, it is found that the estimation of $J_{\rm c}$ from the AC susceptibility depends on the AC magnetic field. It is speculated that the reversible fluxoid motion is more prominent at low AC magnetic fields than assumed in Campbell's model.

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