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Third harmonics due to surface barrier in high-temperature superconductor

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The influence of surface barrier on the third harmonics ac susceptibility (χ_3) is studied numerically. The surface barrier is described by a critical current density in surfaces which are higher than the inside one. The model can act as the critical state one, the flux creep one, or the flux flow one when temperature (or field) changes. The numerical results based on the model are more close to the popular experimental data probing the harmonics as a function of temperature (or field). Besides, the surface barrier will lead to new peaks in the real and imaginary parts of the third harmonics, which are the finger signature of the surface barrier. Comparison of the peaks with those of the real part of elemental harmonic shows that they are located at the same temperature where dips in χ' caused by the surface barrier occur, which is in well agreement with experiments. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1851413]

I. INTRODUCTION

Surface barrier is important in understanding irreversible phenomena of superconductors.[1–8] Experiments show that there exists a surface zone with a higher critical current density j_c (larger than the inside one) which may originate from the surface pinning, the Bean–Livingston barrier, or the geometrical barrier.[9–15] We have proposed a model to describe the surface barrier (SB) and studied the influence of SB on the fundamental ac susceptibility (ACS).[16] In this paper, we will study SB's effects on the third harmonic ACS based on the same model. Usually ACS is measured as a function of temperature (or dc field). To understand the observations in experiments, different models have been proposed.[4,17,18] However, it is still worthy to discuss if or not only one of these models can be employed for the whole of an ACS curve in all temperature regions, because the critical state model is effective at low temperatures, the flux creep model at the relatively higher temperatures, and the flux flow model in the regime near T_c. So we proposed a model of power-law flux velocity whose power n is dependent on temperature (and field) [see below Eq. (1)]. The n is large at low temperatures. With the increment of temperature, n decreases and becomes zero at T_c. The model is in contrast with the previous ones (see, for example, Ref. 18 where $n \equiv \sigma$) whose power n is independent of temperature (field). Our model may be more proper to explain the ACS data at different temperatures.

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II. MODEL AND SIMULATION

The essential point of our model is that there are two j_c in a sample: the higher one j_{cs} in the surface zone and the lower one j_{cb} inside the bulk. We consider a one-dimensional case that the sample is infinite in the y and z directions, the field in the z axis penetrates only along the x axis, which is suitable not only for the Bean–Livingston barrier and the surface pinning, but also for the geometrical one of a long (in the y axis) sample with rectangular cross section (in the x-z plane, thickness t in the z axis) in perpendicular field.[9] The bulk width is d_b whose dimension is millimeters for a bulk sample and micrometers for a thin film. We note that the surface width d_s is comparable to the penetration depth λ for the Bean–Livingston barrier, but d_s is nearly half of the sample thickness $(t/2)$ for the geometrical barrier. For the surface pinning barrier, it is also a relatively broad zone. It is clear that $d=2d_s+d_b$. Therefore, we choose $d_s/d_b=0.1$ for different d_b (1 μm–1 mm), and the strength of SB is adjusted by j_{c0s}/j_{c0b} in the simulation. In fact, although d_s/d_b is regulated from 0.1 to 0.001 for $j_{cs}/j_{cb}=10$–100, there is almost no difference in the numerical results.

The material equation is

$$v = v_0(j/j_c)|j/j_c|^n, \tag{1}$$

where v is the flux-line velocity, v_0 is a velocity scale, and j is current density. From Eq. (1) the power law $E(j) = E_0(j/j_c)^{n+1}$ is obtained, which results in the critical state model for $n \to \infty$, the flux creep one for finite n and the flux flow one for $n=0$. The flux diffusion equation is

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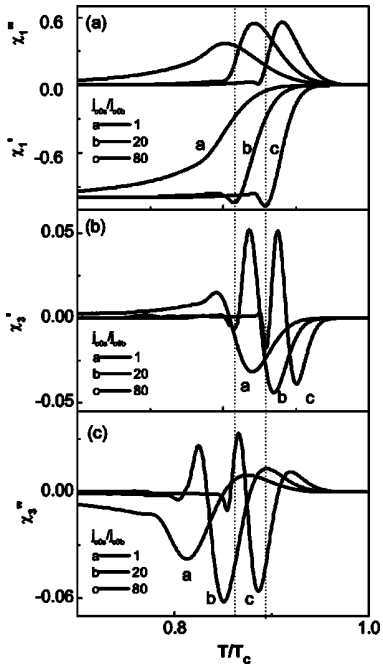

FIG. 1. The harmonics with ($j_{c0s}/j_{c0b}>1$) and without ($j_{c0s}/j_{c0b}=1$) the surface barrier as a function of temperature. The dotted lines show the dips originate from the surface barrier.

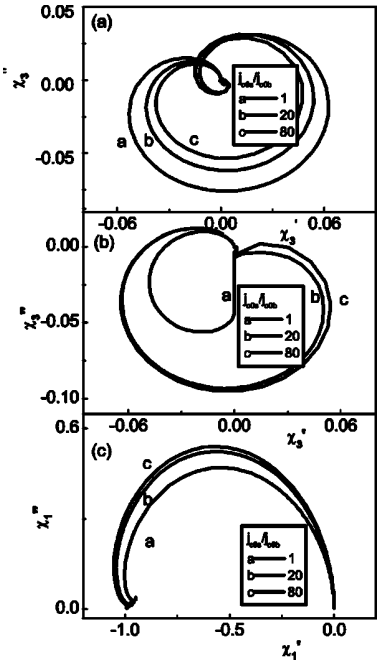

FIG. 2. Polar plots of the third and the first harmonics with ($j_{c0s}/j_{c0b}>1$) and without ($j_{c0s}/j_{c0b}=1$) the surface barrier. (a), (c) The harmonics with temperature power law n. (b) the third harmonics with constant n.

$$\frac{\partial B}{\partial t}=\frac{v_0}{(\mu_0 j_c)^{n+1}}\frac{\partial}{\partial x}\left[\left|\frac{\partial B}{\partial x}\right|^n\left(\frac{\partial B}{\partial x}\right)|B|\right]. \tag{2}$$

The ac susceptibilities can be calculated by

$$\chi_n=\chi_n'-i\chi_n''=\frac{\mu_0}{\pi B_{\mathrm{ac}}}\int_0^{2\pi}M(t)\exp(in\omega t)d(n\omega t), \tag{3}$$

where M is magnetization. The temperature and field dependence of j_c and n are, respectively,

$$j_c=j_{c0}\left[1+\left(\frac{T}{T_c}\right)^2\right]^{-1/2}\left[1-\left(\frac{T}{T_c}\right)^2\right]^{5/2}\frac{B_0}{B_0+|B|}, \tag{4}$$

$$n=n_0\frac{T_c}{T}\left[1-\left(\frac{T}{T_c}\right)^4\right]\frac{B_0}{B_0+|B|}. \tag{5}$$

We note that this n is large at low temperatures but small at high temperatures, which is very important to assure that our model works well in various temperature regimes. In the simulation we let $n_0=5$, $v_0=1$ m/s,[19] $j_{c0b}=5\times10^8$ A/m^2, and $B_0=500$ Gs.

For comparison, the critical state model is also calculated in this paper, where $j_c=j_{\mathrm{cs}}$ or 0 at the surface and $j_c=j_{\mathrm{cb}}$ or 0 in the bulk. For the field dependence, we also use the Kim model $j_c(B)=j_{c0}[B_0/(B_0+|B|)]$.

With the finite difference method, the nonlinear diffusion equation can be numerically solved. And the implicit difference scheme is used for stability.

III. RESULTS AND DISCUSSIONS

The third (χ_3',χ_3'') and the first (χ_1',χ_1'') harmonics with SB ($j_{c0s}/j_{c0b}>1$) and without SB ($j_{c0s}/j_{c0b}=1$) are shown in Fig. 1. If there is no SB, two peaks (we call them primary peaks) appear in both the χ_3' [Fig. 1(b), curve a] and χ_3'' [Fig. 1(c), curve a], respectively, which is similar to the previous results.[20,21] Accordingly, χ_1' and χ_1'' [Fig. 1(a), curve a] have no dips.[16] We can see that the new feature occurs when SB is considered. The most important one is that additional and smaller negative peaks come out in χ_3' and χ_3'', respectively. When SB becomes stronger, two or more small peaks appear. Besides, because SB can hold back the entrance of the flux lines and only at higher temperatures the flux lines can penetrate into the sample, the peaks shift to higher temperatures with the increasing barrier strength. On the other hand, the primary peaks are not monotonically increasing with j_{c0s}/j_{c0b} though they are all in some measure larger than the ones without SB. When $j_{c0s}/j_{c0b}>20$, the heights of the two primary peaks reverse. This is similar to the sign reversal effect predicted in Ref. 17, where the third harmonics (both the real and the imaginary parts) change sign in transition from the geometrical barrier to the bulk pinning. What happened at the temperature where the additional peaks occur in the third harmonics? By comparing Fig. 1, one can easily see that the corresponding dips in χ_1' just take place at the same temperature where the χ_3' peaks occur, as indicated by the dotted lines. The dips in χ_1' indeed have been observed by ACS and Hall array measurements.[12,16] Therefore, we conclude that the additional and smaller negative peaks arise from SB.

As mentioned above, the velocity v of the flux lines (the material equation) changes with temperature and field because n is dependent on T and B. For the ACS curves in Fig. 1, at low temperatures where v is very small, the critical state model ($v=0$) is proper, where increasing temperature flux lines move more and more faster, flux creep model goes into effect, and near T_c the flux lines will flow and the linear material equation should be taken into account. Therefore the

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ACS curves are, in fact, calculated by the critical state, the flux creep, and the flux flow models as temperature goes up. This is very different from the reported results, where either the critical state model or the flux creep one was used for the whole of a $\chi(T)$ curve.[18,22]

Shown in Fig. 2 are the polar plots $\chi_1''-\chi_1'$ and $\chi_3''-\chi_3'$. It is seen that the results in Figs. 2(a) and 2(c) are also different from the reports in Refs. 4 and 18. The cardiodids which traverse in clockwise sense upon decreasing temperature are distorted. In fact, the distortion results from SB and the alteration of the flux creep velocity due to temperature. To confirm this understanding, we calculated the plots $\chi_3''-\chi_3'$ in terms of the so-called whole critical state model (n is infinite) which is suitable at any temperatures, including $T \approx T_c$ where $n=0$ [see Fig. 2(b)]. It is noted that these cardiodids are quite similar to the reports.[4,18]

IV. SUMMARY

In summary, we have used a model to study the influence of SB on the third and the first harmonics of ACS. The model can act as the critical state one, the flux creep one, or the flux flow one when temperature (or field) changes, which is more close to the usual situation in experiments. Simulation shows that SB has its own characteristic peaks (or dips) in the third harmonics, which can be considered as a finger signature of SB. By comparing the peaks with those in the real part of elemental harmonic, we find that the peaks are at the same temperature where dips in χ' caused by the SB occur, which coincides with experiments.

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