Properties of thermally activated flux motion in MTG-GdBCO measured by AC susceptibility

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Abstract. Thermally activated flux motion in melt texture growth Gd-Ba-Cu-O bulk has been studied by ac susceptibility measurements. The irreversibility line B_{irr}(T) and the intrinsic pinning energy U(T, B) of the bulk have been extrapolated from the measurements, which can be written as

\[ B_{irr}(T) = B_c (1 - T/T_c)^n \]

where \(80T < B_c < 98T\) and \(1.4 < n < 1.48\), and

\[ U(T, B) = U_{c}(1 - T/T_c)^{1.5} B^{-0.8} \]

where \(t\) is the reduced temperature \(T/T_c\) and \(B\) is magnetic field, respectively. Also experiments reveal that peak temperature \(T_p\) of the out of phase component \(\chi''\) shifts towards low temperature region with the decreasing of the ac field. All these results suggest that the thermally activated flux motion process might be based on the Bean’s critical state model, rather than thermally assisted flux-flow (TAFF) process.

1. Introduction
Many efforts have been devoted to develop light rare earth barium-cupper-oxide (LReBCO) bulks (LRe = Nd, Sm, Eu and Gd) by melt textured growth process, which are believed to be a new generation of high temperature superconductor bulk materials exhibiting a superior properties of the flux trapping to the Y-Ba-Cu-O ones. Even though the melt texture growth of the LReBCO compounds processed in air often leads to solid solution phase in the bulk, i.e. the Ba sites are partly replaced by the LRe elements, which results in a deteriorate of superconducting transition properties, the LRe/Ba substitution defects dispersed in LReBa₂Cu₃O₇₋δ(LRe123) matrix might act as an additional source of strong pinning centers which might lead to a higher pinning energy for the flux motion. It has been proved that MTG Gd-Ba-Cu-O bulks can trap even larger magnetic fields and undertake higher critical current compared with MTG Y-Ba-Cu-O bulks[1-2], and, consequently, as a promising candidate for engineering applications it have been paid much attention in recent years [3-5]. Although many efforts have been paid on how to optimize the fabrication process of this type of bulk, the knowledge of the vortex dynamics for this system seems to be still in shortage at present time.

Due to the nature of the anisotropy layer structure, and of the extremely short coherent length, high-Tc superconductors have presented a prominent magnetic relaxation property, even though there are sufficient strong pinning centers randomly distributed within the body. The nature of the thermally activated flux motion could be identified according to the ratio of the intrinsic pinning energy to thermal activation, i.e. \(U(T, B)/k_B T\). In the case of \(U(T, B)/k_B T \approx 1\), the effective pinning energy is relatively low, and even a small driving force can produce a directional movement of the flux lines, a process that is called thermally assisted flux flow (TAFF), which corresponds to a linear flux motion

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dissipation [6]. When the pinning energy $U$ is very much larger than $\kappa T$, i.e. $U(T,B)/k_BT \gg 1$, larger driving force is needed for the flux lines to overcome their potential wells and a nonlinear dissipation is responsible to this process, which is referred to as a thermally activated flux creep (TAFC) mechanism [7]. In H-T phase diagram, TAFC process occurs in the vortex-solid region below the irreversibility line $B_{irr}(T)$, while TAFF process appears in the vortex liquid region between the irreversibility line and the upper critical field $H_{c2}(T)$ line. Therefore, giving a thorough research on dissipative behavior induced by the thermally activated flux motion is an important precondition for studying the irreversibility line behavior for high-$T_c$ superconductors. Although ac susceptibility measurements have been widely used to study vortex dynamics of the high temperature superconductors, there are still some discrepancies concerning the nature of the ac response [8-10].

In this paper systemic study of ac response of vortex system in a high quality MTG Gd-Ba-Cu-O bulk sample has been performed for the first time. From a series of ac susceptibility experiments, the irreversibility line $B_{irr}(T)$ and intrinsic pinning energy $U(T,B)$ have been obtained. More importantly, it is found that the thermally activated flux motion in Gd-Ba-Cu-O single domain exhibits a character of the collective flux creep in the critical-state model.

2. Experiment

2.1. Sample fabrication

Single-domain Gd-Ba-Cu-O bulks with diameter of 22mm were fabricated in air using top-seeded melt-textured growth process. Microstructure analysis by X-ray diffraction shows that only (00l) peaks ($l = 2, 3, 4, 5, 6, 7$) are visible, which indicates a well c-axis orientation structure for the sample. The levitation force of this sample was also measured and the maximum levitation density 15 N/cm$^2$ was showed, suggesting a high quality of the critical current for the sample. The superconducting transition temperature $T_c$ is about 87.3 K, a little bit lower than 90K. This might arise from Gd-Ba substitution, which leads to a degradation of the superconductivity of the sample. The details of the fabrication are given in Ref. 11.

2.2. Measurements and results

The ac susceptibility responses have been systemically measured by using PPMS-9 system (Quantum Design Inc). In experiments, dc magnetic fields of $\mu_0H_{dc} = 0, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0$ T, and ac field of $\mu_0H_{ac} = 0.2, 0.5, 1, 3, 5, 7, 9$ G, and ac field frequencies of $f = 20, 55, 148, 403, 1097, 2981$ Hz, were applied respectively. Both dc magnetic fields and ac fields are parallel to the c axis of the sample.

Figure (1) shows the experimental results of the ac susceptibility $\chi_{ac}$ as a function of temperature at various dc magnetic fields, and with $f = 2981$ Hz and $\mu_0H_{ac} = 7$G. Similar response behavior has also been obtained with other frequencies and other ac fields. As shown in figure (1), the curves of the in phase component $\chi'(T)$ are almost parallel to each other at different dc fields, only a slight broadening is observed for the field of 5 T. It contrast sharply with the one obtained in MTG Y-Ba-Cu-O bulks, where a remarkable broadening of the in phase component $\chi'(T)$ has been found even though as $\mu_0H_{dc} \leq 1$ T, and it also suggests that there is a good alignment of the crystal grains along c-axis direction within the sample, and there are a few superconducting weak links within the sample. Therefore the observed ac response could be thought of coming from the pinning vortices system, not from the Josephson vortices. It can be also observed from figure (1) that there is a increasing of the magnitude in the peak of $\chi'(T)$ with the applied dc magnetic field, which can be thought of the vortices loss increased proportionally with the applied external dc field. However, further investigation is needed for fully understanding of this phenomenon.

An important characteristic feature for high temperature superconductors is the so-called irreversibility line $B_{irr}(T)$, which determines the boundary between vortex glass and vortex liquid state.
Figure 1. In-phase and out-of-phase components of the ac susceptibility measured at $\mu_0H_{ac} = 7\,G$ and $f = 2981\,Hz$, for $\mu_0H_{dc} = 0, 0.1, 0.2, 0.5, 1.0, 2.0,$ and $5.0\,T$ (from right to the left).

in the H-T plane. The knowledge about $B_{irr}(T)$ is most important for understanding flux dynamics in high temperature superconductors. It can be deduced from the ac susceptibility measurements. Although there is still controversy on its precision for the onset of the irreversibility, this criterion is still being widely adopted for its convenience [8, 12, 13]. By using this method, we constructed the irreversibility lines for different frequencies and presented them in figure (2), where the symbols denote experimental data and the lines are fittings with the form of $B_{irr}(T) = B_0(1-\tau)^n$ with $1.4 < n < 1.48$ and $B_0 = 80 - 987^\circ$. It also reveals that irreversibility lines $B_{irr}(T)$ shift towards lower temperature region when measuring frequencies is becoming lower. Figure (3) presents the $\chi'(T)$ and $\chi''(T)$ measured with various frequencies and fixed field of $\mu_0H_{dc} = 5\,T$ and $\mu_0H_{ac} = 7\,G$. It presents that the peak of $\chi''(T)$ shifts to high temperature region as frequency increased, similar to the response behavior presented in figure (2).

The experimental results showed in figure (2) and (3) illustrate the response behavior with two features that as ac field frequency decreasing both irreversibility line and the peak of ac susceptibility
shift towards the lower temperatures, and that the irreversibility field at zero temperature $B_{irr}(0)$ can reach to 80T – 98T, much higher than the one obtained from YBCO[13] and PrCeCuO[8].

In order to get more information about the nature of the ac response, the temperature dependence of the imaginary part of ac susceptibility $\chi'(T)$ was also measured at various amplitude of ac field, which were 0.2, 0.5, 1.0, 3.0, 5.0, and 9.0 G respectively; and the frequency was fixed at 2981 Hz. Figure (4) shows the experimental results of $\chi'(T)$, and there are also two features worth mentioned. Firstly, when increasing the ac field amplitude, the peak of the $\chi'$ curve correspondingly becomes higher, similar to those observed in the $\chi'$ curve. We consider this behavior to be the calibration errors in the measurement system, and, secondly, the peak temperature $T_p$ in $\chi'$ shifts to lower temperatures as $\mu_0H_{ac}$ increased, a similar response behaviour that has been observed previously by other groups [16, 17]. This result implies that the ac response of the vortex system is due to thermally activated flux creep, and more detailed discussion about it will be presented in next section of this paper.

In figure (5), we summarize the measuring data to show the effects of frequency $f$ and dc field $H_{dc}$ on the peak temperature $T_p$, where the relationship between frequency and the peak temperature has been plotted as $-\ln f$ vs. $(1 - T_p / T_c)^{3/2} / T_p$. It is shown that the data measured at each different dc field can be reasonably fitted by a straight line, and the slope of the fitting lines decreases with the increasing of the dc field. Similar results have also been observed in other high temperature superconductors such as YBCO [16, 17], NdCeCuO [9], and PrCeCuO [8]. According to Anderson’s flux creep theory, the slopes of these fitting straight lines directly correspond to the flux pinning energy $U(B)$, by which the magnetic field dependence of $U(B)$ can be obtained from the experiment.

![Figure 5](image_url)

**Figure 5.** Plot of $-\ln f$ versus $(1 - T_p / T_c)^{3/2} / T_p$ for various dc fields.

3. Discussion

3.1. Flux creep process in critical state

As mentioned in Section 1, TAFF process occurs in the vortex liquid region in H-T phase diagram, which is located in the region between the upper critical field line $H_{c2}(T)$ and the irreversibility field.
line $H_{irr}(T)$. As for the TAFC process, it exists in the region below the irreversibility line, and is characterized with a nonlinear flux motion dissipation. Therefore, the macroscopic responses of these two types of flux motion to an external magnetic field (especially an ac field) are very different from each other. Magnetic response of the TAFF regime to a strong dc magnetic field superimposed with a low amplitude ac field was studied in Ref. 6. Starting from the one-dimensional linear equation of flux diffusion, the ac field profile in a superconducting slab can be expressed as

$$b(x) = b_m \exp(-x / \delta)$$

where $b_m$ is the amplitude of ac field, $\delta$ is skin penetration depth of the field and is expressed as

$$\delta = \left(\frac{D_o}{\pi f}\right)^{1/2}$$

where $D_o$ is the magnetic-flux diffusion constant and is expressed as

$$D_o = 2\omega_0 \left(\frac{U}{kT}\right) \left(\frac{B}{\mu_0 J_c}\right)^w \exp\left(-\frac{U}{kT}\right)$$

In expression (3), $w$ is jump distance of flux bundle, $r_p$ is pinning range of the flux bundle, $k$ is Boltzmann constant, and $U$ is the function of pinning energy depending on $B$ and $T$. Because of the linear character of the diffusion, the real and imaginary components of the ac susceptibility can be calculated as

$$\chi' = \frac{\delta}{2l} \cdot \frac{\sinh(2l/\delta) + \sin(2l/\delta)}{\cosh(2l/\delta) + \cos(2l/\delta)}$$

(4a)

$$\chi'' = \frac{\delta}{2l} \cdot \frac{\sinh(2l/\delta) - \sin(2l/\delta)}{\cosh(2l/\delta) + \cos(2l/\delta)}$$

(4b)

where $l$ is the sample thickness perpendicular to the external magnetic fields. From expression (4), it is obvious that ac response is independent on the ac field amplitude $b_m$. However, according to Bean’s critical state model, the ac field inside the superconductor slab in one dimension case can be expressed as

$$b(x,0) = b_m - \mu_0 J_c x$$

(5)

and the critical penetration depth can be easily derived from Eq. (5) as

$$\delta_c = \frac{b_m}{\mu_0 J_c}$$

(6)

and the expressions of the ac susceptibility can be derived according to the TAFC mode [12]:

$$\chi' = \begin{cases} \frac{\delta_c}{l} - \frac{\delta_c^2}{3l^2} - \frac{1}{3\delta_c}, & 0 \leq \delta_c \leq l \\ -\frac{1}{3\delta_c}, & l \leq \delta_c \leq 2l \end{cases}$$

(7a)

$$\chi'' = \begin{cases} \frac{\delta_c}{2l} - \frac{\delta_c^2}{4l^2}, & 0 \leq \delta_c \\ -\frac{1}{3\delta_c} + 1 - \frac{\delta_c}{2l} + \frac{\delta_c^2}{12l^2}, & l \leq \delta_c \leq 2l \\ \frac{\delta_c}{3l} \cdot \frac{\delta_c}{3l}, & 2l \leq \delta_c \leq 2l \end{cases}$$

(7b)
Equation (7) presents the ac susceptibility with a strong ac field amplitude $b_m$ dependent behavior, and its peak position when
$$\delta_c = \frac{\tau}{f}$$
is satisfied.

According to (6), (7) and (8), it can be found that when the amplitude of the ac field $b_m$ is increased the balance condition of equation (8) is broken, and the peak of $\chi''$ would disappear. In order to maintain the appearance of the peak of $\chi''$ the ratio of $b_m$ to $J_c$ in equation (6) have to be kept as a constant, and it could be realized by decreasing the temperature, equivalently to enhance the $J_c$. The measuring data showed in figure (4) can be described well by above discussion, which provides an evidence that the ac response of the Gd-Ba-Cu-O bulk is characterized as the process based on the TAF model.

Based on the experimental data on the peak temperature of $\chi''$ at various ac field amplitudes, the temperature dependence of $J_c(T)$ can be obtained according to equations (6) and (8). Figure (6) presents the plot of $J_c$ vs. $T$ obtained by combination of the experimental data and the theoretical calculation. The theoretical values come from $J_c = J_0[1 - k_B T U(T,B)]$ (for $H_d = 17$ K, and $n = 1.7$). In figure (6), the above current expression fits the measured data reasonably well, suggesting further that the ac response characteristics of our sample can be described in terms of TAF model.

3.2. Pinning energy of Gd-Ba-Cu-O bulk

According to the Kim-Anderson model of thermally activated flux creep, the critical current density can be expressed as
$$J_c = J_0[1 - \frac{k_B T}{U(T,B)} \ln\left(\frac{f_o}{f}\right)]$$

where $J_0$ is the critical current density at $T = 0K$, $f_0$ and $f$ are the characteristic frequency of thermal vortex vibration and hopping rate for current-induced movements of flux lines, respectively, and $U(T,B)$ is intrinsic pinning energy which depends on the temperature $T$ and applied magnetic field $B$.

In the vicinity of the irreversibility line where the critical current density $J_c$ approaches zero, an expression below can be easily derived from equation (9) by taking into account the relation
$$\ln\left(\frac{f_o}{f}\right) = \frac{U(B_{irr})}{k_B} \frac{U(T)}{T}$$

According to Eq. (10), if the $U(T)$ relation is given, one can obtain the magnetic field dependence of $U(B)$ from relevant experimental data. Yeshurun and Malozemoff [18] showed that pinning energy $U(T)$ for Y-Ba-Cu-O could be written as $U(T) \propto (1 - T/K)^{3/2}$, based on which they also proved that the irreversibility field taken the form $B_{irr}(T) \propto (1 - T/K)^{3/2}$. This expression is consistent with our experimental results shown in figure (2), therefore, we will adopt the form $U(T) \propto (1 - T/K)^{3/2}$ to calculate $U(B)$.

According to the principle of ac susceptibility measurement, the maximum in the out-of-phase component occurs when $f = 1$, where $f$ is the hopping rate of flux lines, and $\tau$ is the drive period of the ac field. Therefore, we can derive flux hopping frequency for the peak position of $\chi''$ from the ac field frequency. Comparing Eq. (10) with the linear dependence $-\ln f \propto (1 - T/K)^{3/2} T^{-1}$ shown in figure (5), it can be found that the slopes of the straight lines $-\ln f \propto (1 - T/K)^{3/2} T^{-1}$ correspond to the values of $U(B_{irr})/k$. In figure (5), measured data for each dc field are well fitted by straight lines,
completely satisfied with the linear relation given by Eq.10. Therefore, the field dependence of pinning energy $U(B) \approx H$ can be obtained from the slope of fitting line for each dc field. Displayed in Figure (7) are the $U(B)$ values obtained at six different dc fields. The solid line is fits to a power law $U(B) \approx B^{-0.8}$, which is similar to the form $U(B) \approx B^{-4}$ obtained from the Yeshurun-Malozeemoff theory [18].

4. Conclusions
Thermally activated flux motion in MTG Gd-Ba-Cu-O bulk has been studied by using ac susceptibility experiments. It is found that the irreversibility line is given by $B_{irr}(T) = B_0(1-T/\mu T)^n$, with $B_0 = 80$ T – 98 T, and $1.4 < n < 1.8$. While the intrinsic pinning energy can be expressed as $U(T, B) = U_0(1-T/\mu T)^z B^{-0.8}$. These results are similar to those obtained in YBCO single crystal based on the Yeshurun-Malozeemoff theory, and demonstrate that flux motion in Gd-Ba-Cu-O single domain bulk possesses the characteristics of collective flux creep. It is also found that the complex ac susceptibility is influenced by the ac field amplitude. This is another phenomenon associated with flux creep in the critical-state model. In addition, the experimental results exhibit the unusual irreversibility behavior of MTG Gd-Ba-Cu-O. The irreversibility field at $T = 0$ locates between 80 T and 98 T, which is the largest value found in high temperature superconductors to date, and implies prospects for wide applications of MTG Gd-Ba-Cu-O.

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