International Journal of Modern Physics B
Vol. 17, Nos. 4, 5 & 6 (2003) 655–660

World Scientific
www.worldscientific.com

STUDY OF THE VORTEX DYNAMIC IN MGB_2 BY HARMONIC SUSCEPTIBILITY MEASUREMENTS

C. SENATORE, M. POLICHETTI, D. ZOLA, T. DI MATTEO and S. PACE
Dipartimento di Fisica "E. R.. Caianiello", Università degli Studi di Salerno & I.N.F.M., Via S. Allende, Baronissi (SA), I-84081, Italy

G. GIUNCHI, S. CERESARA and G. RIPAMONTI
EDISON S.p.A., Foro Bonaparte 31, Milano, I-20121, Italy

In order to investigate the flux line dynamic in the recently discovered MgB_2 superconductor, we have measured the ac magnetic susceptibility as a function of the temperature T and the ac field frequency f on a bulk sample. In particular we have analysed the fundamental and the third harmonics $\chi_{1,3}(T)= \chi'_{1,3}(T)+ i\chi''_{1,3}(T)$ by comparison of the experimental data with both analytical and numerical results. We show that in the temperature range below $T_p(\chi''_1)$ (i.e. the peak temperature of the imaginary part for the fundamental harmonic) the measured curves for $\chi_3(T)$ do not agree with the curves predicted by the Bean model for the critical state, and that the shape of the third harmonic, both in the real and the imaginary part, is strongly affected by the frequency f, as a consequence of the thermally activated vortex motion in a non linear flux diffusion regime. The evidence of this behaviour allows one to estimate the value of the pinning barrier for the analysed sample.

1 Introduction

The recent discovery of superconductivity in MgB_2 with a transition temperature T_c close to 39 K [1] has generated a considerable interest in the field of condensed matter physics, both from the experimental and the theoretical point of view [2-6]. In fact, there are many proposal for potential application of MgB_2, exploiting its high T_c and critical current density (J_c). However, in order to improve the $J_c(B)$ dependence and the other parameters for all potential applications, we need to understand the pinning properties as well as the vortex dynamic.

The study of the dynamics of the flux lines in different regime represents, therefore, a crucial point to fully understand the mechanism governing the magnetic irreversibility and the ac losses [7]; a powerful tool for the investigation of such phenomena is of course provided by using the ac susceptibility technique. In fact this technique enables us to induce changes in vortex dynamic by changing the value of the external parameters, such as the ac field frequency and amplitude, the dc field intensity, the temperature, etc. [8]. In addition to the fundamental response, the higher order harmonics of ac susceptibility can provide much insight into the loss mechanisms and the flux motion [9-12]. The first interpretation comes from the original Bean critical state model [11], which attributes the harmonic generation to the hysteretic, non-linear relationship between the magnetization and the external field due to the flux pinning. More recent studies concern the numerical integration of the non-linear diffusion equation for the internal magnetic field, in its one-dimensional form [9,10]. In particular, the shape of the temperature dependencies of the third harmonic response is related to the dissipative phenomena (flux flow, flux creep, thermally activated flux flow) and a non-universal behaviour is found as the frequency increases [10].

In this work we investigate the flux line dynamic on a MgB_2 bulk sample by measuring the ac magnetic susceptibility as a function of the temperature T and the ac field frequency f. The focus of this paper is the study of the frequency and field dependence of the third harmonic response. In order to recognize the dynamic mechanisms of the observed behaviours we have interpreted data by using both analytical results and numerical simulations and we have estimated the value of the pinning potential U_P.

2 Experimental Results and Discussion

We performed our AC susceptibility measurements on a MgB_2 bulk sample, prepared by EDISON S.p.A., whose dimensions are 25×7×0.8 mm^3. The temperature dependencies of both the first and the third harmonics have been measured changing the temperature with a rate $\Delta T/\Delta t$ = 0.4 K/min., in the range 4.2÷45 K, at different field amplitudes (4, 8, 16 G) and frequencies (7, 27, 107, 1607, 5007 Hz). The curves of $\chi'_1(T)$ show a quite sharp transition with a T_c=35.2 K, its width being about 1 K. It is well known [11] that at the peak temperature in the $\chi''_1(T)$ the critical current can be approximated as

$$J_c = \frac{H_{ac}}{d} \tag{1}$$

where d is the sample size; so, by using the field and temperature dependencies for J_c known in literature [6,13,16], we can estimate the critical current density at T= 0 K, which is $J_c(0\text{ K}) \approx 10^6$ A/cm^2.

Nevertheless, we notice that the fundamental harmonic is just slightly affected by changes in frequency, while, on the contrary, a pronounced dependence appears in the third harmonic measurements. To analyse the behaviour of the $\chi_3(T)$ experimental curves and connect it with flux dynamic phenomena, we need to consider some models reported in literature.

Since the magnetic experimental data have a clear frequency dependence, a simple critical state description is not suitable [12]. However, a first comparison with the curves predicted by the Bean model is useful to individuate the regions of the $\chi_3(T)$ data that show the presence of dynamical regimes. In fact, while the real part of χ_3 as calculated in the critical state model remains zero since the full penetration is reached, the experimental curves show, in the range of frequencies of our measurements, a negative peak at lower temperature than the positive peak predicted by the Bean model. The main feature of the experimental curves is that, by increasing the frequency, not only the position of the positive and negative peaks moves toward higher temperatures, but also the ratio between the heights of the peaks, in absolute value, changes; an analogous behaviour is also observed in the imaginary part of χ_3. The only way to explain these evidences is to consider the presence of dynamical regimes connected to the thermally activated flux motion. A first look to our $\chi_3(T)$ measurements shows a qualitative agreement with the results obtained by numerical simulation of magnetic diffusion processes [10]. In particular, the frequency behaviour of the measured curves in the range 7÷107 Hz (Fig. 1) is well reproduced by the curves calculated in a pure flux creep regime within the framework of collective pinning model. In these curves the absolute height of the $\chi'_3(T)$ negative peak decreases, while the height of the positive one grows up. The good qualitative agreement with the numerical simulations [10] suggests that at least at these frequencies the only relevant dynamical effect is the flux creep, which eventually is superimposed to an underlying frequency independent critical state.

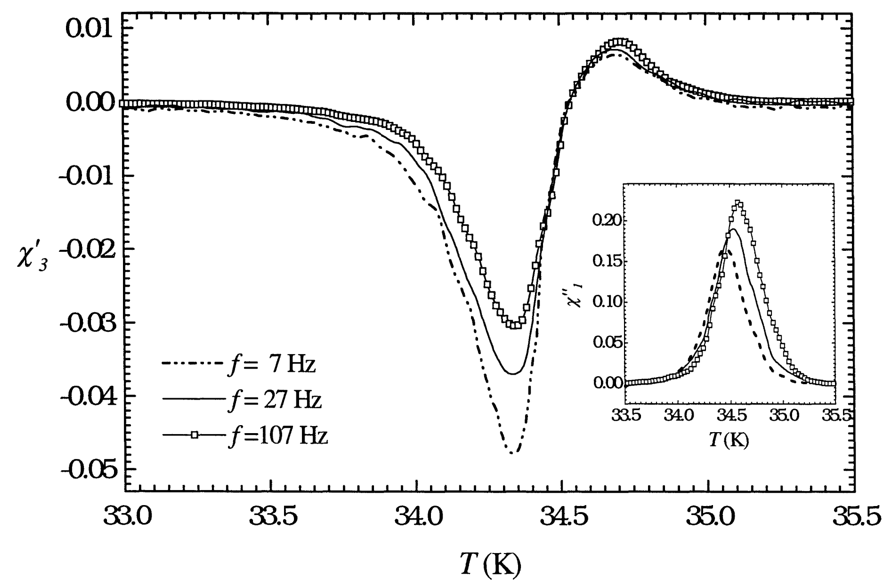

Figure 1. Temperature dependence of χ'_3 measured at H_{ac}= 8 G and f = 7, 27, 107 Hz; Inset: temperature dependence of χ'_1 measured at the same ac field and frequencies.

In the range of frequencies 1007–5007 Hz in the $\chi''_3(T)$ curves a bump appears at a temperature lower than $T_p(\chi''_3)$, i.e. the one of the principal peak (Fig. 2). Increasing the amplitude of the ac field this bump manifests itself as an additional peak at temperature $T_B(\chi''_3)$, which moves toward lower temperatures with a rate comparable with that of the principal peak (Fig. 3). On the contrary, as the frequency increases, also $T_p(\chi''_3)$ increases while it is hard to appreciate a clear variation in $T_B(\chi''_3)$. This suggests that the bump, which for low frequencies is probably hidden under the principal peak, appears for higher frequencies, when the principal peak is shifted to higher temperatures. Therefore it is possible to suppose that also in the $\chi''_1(T)$ curves the spurious peak corresponding to the bump could be hidden under the $\chi''_1(T)$ principal peak. An eventual additional spurious phase which originates this bump might have a different vortex dynamic, and then a different J_c. This could justify the different behaviour of the two peaks in $\chi''_3(T)$ curves changing the frequency.

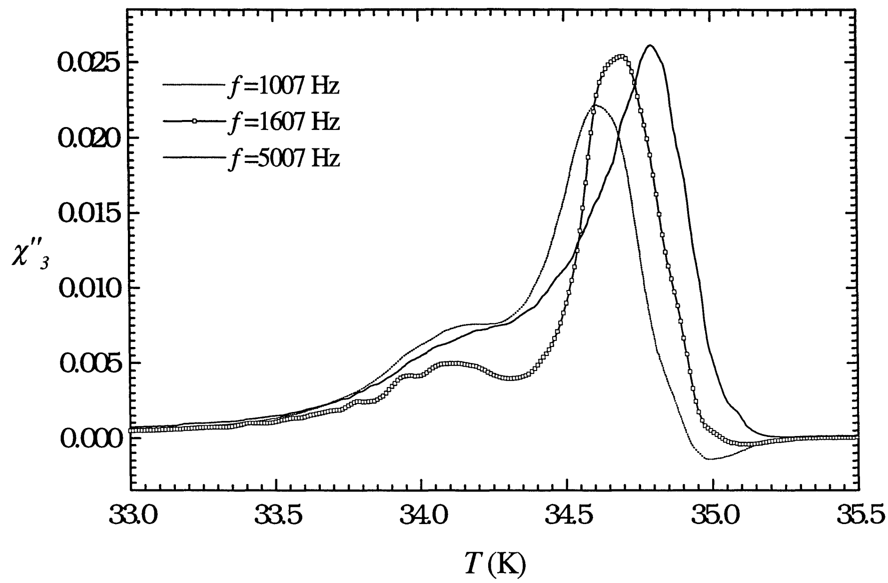

Figure 2. Temperature dependence of χ''_3 measured at H_{ac}= 4 G and f = 1007, 1607, 5007 Hz.

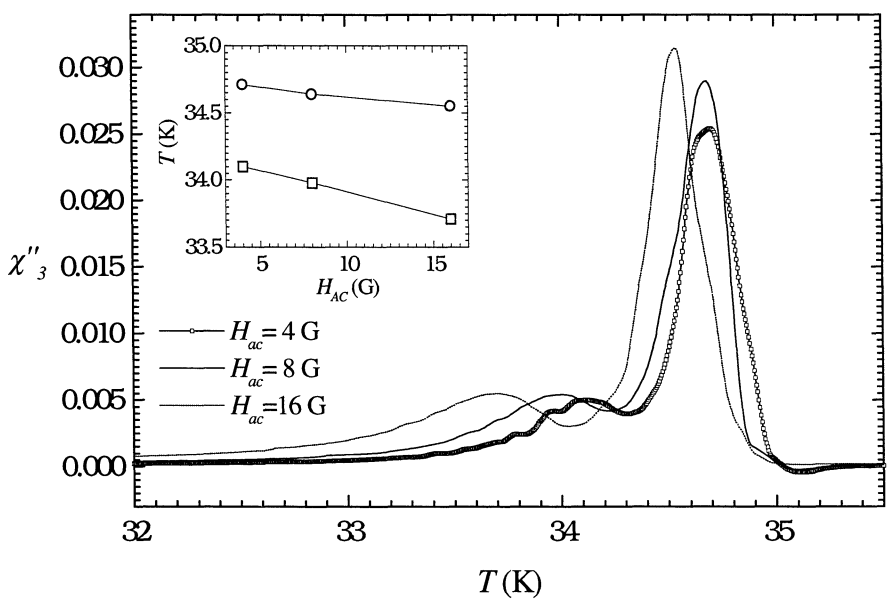

Figure 3. Temperature dependence of χ''_3 measured at f = 1607 Hz and H_{ac}= 4, 8, 16 G; Inset: behaviour of $T_B(\chi''_3)$ (open squares) and $T_p(\chi''_3)$ (open circles) as a function of H_{ac}.

The study of vortex dynamic carried out by using the third harmonic analysis has shown the presence of thermally activated flux motion. This allows us to apply the method elaborated by Ren *et al.* [14] to estimate the thermal activation energy U_P. In fact, supposing that the velocity of flux lines obeys the Arrhenius law and solving the magnetic field diffusion equation perturbatively, the criteria for the peak in $\chi''_1(T)$ can be obtained [15]:

$$U_P(T_P, H_{dc}, j = H_{ac}/d) = T_P \ln\left[1 + \frac{1}{f\,t_0}\right], \qquad (2)$$

where t_0 is a time scale that represents the attempt time for the flux thermally activated motion.

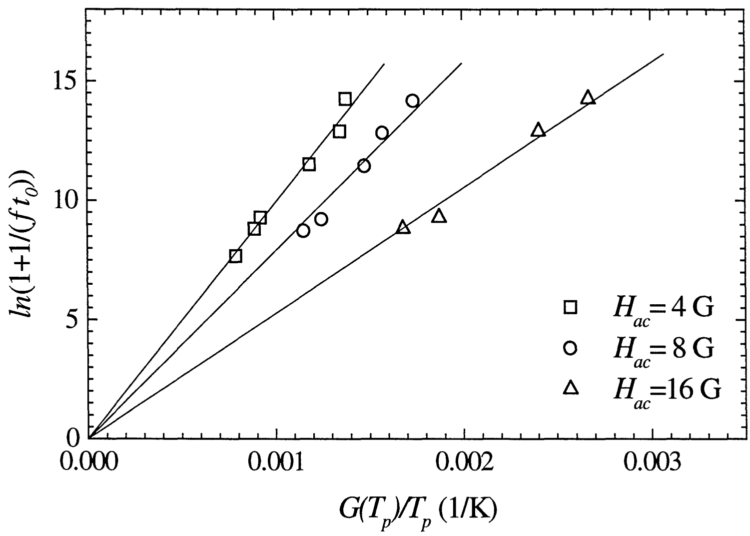

Figure 4. The peak temperatures in $\chi''_1(T)$ curves, $T_p(f, H_{ac})$, are plotted as $ln[1+1/(f\,t_0)]$ vs $G(T_p)/T_p$ for H_{ac}= 4, 8, 16 G. The symbols are the data while the solid lines are fitted curves.

All of our $T_p(f, H_{ac})$ data are summarized in Fig. 4 by plotting $ln[1+1/(f\,t_0)]$ vs $G(T_p)/T_p$, where $t_0 = 0.1\mu s$ is a time scale and $G(T_p)=[1-(T_p/T_c)^4]$ is the scaling function accounting for the temperature dependence of the pinning barrier U_P [16], i.e.

$$U_P(j, H_{dc}, T_p) = U_P(j, H_{dc}, T_p = 0\ \mathrm{K})G(T_p).$$

From eq. (2) it is clear that the slopes of the fitted straight lines in Fig. 4 represent the activation barriers $U_P(j = H_{ac}/d,\ 0\ \mathrm{K})$; so we can extrapolate the value of the pinning barrier at $j = 0$ by using the Anderson-Kim relationship $U_P(j) = [1-(j/j_0)]$, and the calculated value is $U_P(0\ \mathrm{K}) \approx 1$ eV. The small value of $U_P(0\ \mathrm{K})$ respect to what is found in literature [17] justifies the evidence of clear thermally activated phenomena in the range of temperatures analysed.

3 Conclusions

In summary, we have analysed in this work the ac field frequency and amplitude dependencies of the susceptibility harmonics. By comparison with the critical state description we have evidenced the contribution of dynamical processes; in fact, the experimental data show that a change in frequency modifies the shape of the $\chi_3(T)$ curves and this result is in agreement with numerical simulations of flux diffusion, suggesting the presence of thermally activated vortex motion. Furthermore a spurious phase in the sample has been detected by the $\chi''_3(T)$ curves study and this confirms that the third harmonic analysis is an instrument of investigation more sensitive than fundamental one. Finally the information obtained with the help of the third harmonic has allowed us to estimate the value of the pinning barrier for a more complete characterization of the sample.

Acknowledgements

We want to thank Mr. A. Ferrentino for his technical support.

References

1. Nagamatsu J., Nakagawa N., Maranaka T., Zenitani Y. and Akimitsu J., *Nature* **410** (2001) 63.
2. Bugoslavsky Y., Perkins G. K., Qi X., Cohen L. F. and Caplin A. D., *Nature* **410** (2001) 563.
3. Bugoslavsky Y., Cohen L. F., Perkins G. K., Polichetti M. and Caplin A. D., *Nature* **411** (2001) 561.
4. Finnemore D. K., Ostenson J. E., Bud'ko S. L., Lapertot G., Canfield P. C., *Phys. Rev. Lett.* **86** (2001) 2420.
5. Kortus J., Mazin I. I., Belashchenko K. D., Antropov V. P. and Boyer L. L., *Phys. Rev. Lett.* **86** (2001) 4656.
6. Buzea C. and Yamashita T., *Supercond. Sci. Technol.* **14** (2001) 115.
7. Clem J. R., *Magnetic Susceptibility of Superconductors and Other Spin Systems*, eds. Hein R. A., Francavilla T. L. and Liebenberg D. H. (New York, Plenum Press, 1991).
8. Gömöry F., *Supercond. Sci. Technol.* **10** (1997) 523.
9. Qin M. J., Ong C. K., *Physica C* **319** (1999) 41.
10. Di Gioacchino D., Celani F., Tripodi P., Testa A. M., Pace S., *Phys. Rev. B* **59** (1999) 11539.
11. Bean C. P., *Rev. Mod. Phys.* **2** (1964) 31, *Phys. Rev. Lett.* **8** (1962) 250.
12. Polichetti M., Adesso M. G., Di Matteo T., Vecchione A., Pace S., *Physica C* **332** (2000) 378.
13. Dhalle M., Toulemonde P., Beneduce C., Musolino N., Decroux M. and Flukiger R., cond-mat/0104395.
14. Ren C., Ding S. Y., Zheng Z. Y., Qin M. J., Yao X. X., Fu Y. X., Cai C. B., *Phys. Rev. B* **53** (1996) 11348.
15. Blatter G., Feigel'man M. V., Geshkenbin V. B., Larkin A. I. And Vinokur V. M., *Rev. Mod. Phys.* **66** (1994) 1125.
16. Hagen C. W. and Griessen R., *Phys. Rev. Lett.* **62** (1989) 2857.
17. Qin M. J., Wang X. L., Liu H. K., Dou S. X., cond-mat/0104112.