EUROPHYSICS LETTERS

OFFPRINT

Vol. 65 • Number 4 • pp. 540–545

Current-dependent crossover in the flux dynamics of MgB_2 thin films

* * *

S. L. Prischepa, M. Salvato and L. Maritato

Published under the scientific responsibility of the
EUROPEAN PHYSICAL SOCIETY
Incorporating
JOURNAL DE PHYSIQUE LETTRES • LETTERE AL NUOVO CIMENTO

EUROPHYSICS LETTERS 15 February 2004
Europhys. Lett., **65** (4), pp. 540–545 (2004)
DOI: 10.1209/epl/i2003-10123-2

Current-dependent crossover in the flux dynamics of MgB_2 thin films

S. L. Prischepa(*), M. Salvato and L. Maritato
Dipartimento di Fisica "E. R. Caianiello", Università di Salerno and INFM/Coherentia - Via S. Allende, I-84081 Baronissi (SA), Italy

(received 19 June 2003; accepted in final form 10 December 2003)

PACS. 74.78.-w – Superconducting films and low-dimensional structures.

Abstract. – We have investigated the dissipative behaviour of MgB_2 textured thin films at different perpendicular magnetic fields H and bias currents J, to study activation energy dependencies $U(J)$ and $U(H)$. For $J < J^*$, where J^* is a magnetic-field–dependent crossover current, activation energies are weakly current dependent, $U(J) \approx$ const, while, for $J > J^*$, $U(J) \sim -\ln J$. At $J < J^*$, the magnetic-energy dependencies are logarithmic, $U(H) \sim -\ln H$, while for $J > J^*$, $U(H) \sim H^{-1}$, up to $\mu_0 H \approx 5\,\mathrm{T}$. The $J^*(H)$ curve separates two zones with different vortex dynamics. We discuss the $J^*(H)$ curve in terms of a current-driven transition from a thermally activated flux flow to a flux creep regime. For pronounced disorder, the data suggest the influence of the activation energy distribution on the $U(J)$ and $U(H)$ dependencies.

MgB_2, the binary compound recently discovered to be superconducting, has attracted a lot of research activity to investigate its basic physical properties [1]. The large amount of studies on the superconducting gaps of the two bands [2–4], the superconducting phase diagram [5] and the anisotropy of the system [6–8] has well established many fundamental superconducting parameters.

Many research works have been also dedicated, in view of practical applications, to the study of the current capability and the nature of the pinning in this compound [9–11]. In spite of the low value of the Ginzburg number $Gi \approx 10^{-5}$, which measures the importance of the thermal fluctuactions against the condensation energy, flux creep (FC) effects have been found to strongly influence the dissipative behaviour, especially with increasing external magnetic fields [12]. So far, the dynamic states of the vortices in MgB_2 have been less investigated, especially in the case of *in situ* grown thin films, essential for many electronic applications, which, due to their particular microstructures, can present dissipative properties quite different from the bulk.

In this work, we report the observation of a current-driven pronounced crossover in the vortex dynamics of *in situ* sputtered MgB_2 thin films. At a magnetic-field–dependent crossover current density J^*, both the current, $U(J)$, and the magnetic field, $U(H)$, dependencies of the activation energy show a sudden change which we relate to a transition from a thermally activated flux flow (TAFF) regime to a FC behaviour. The experimental data give also information about the distribution of the pinning activation energies, which seems to be influenced by the disorder present in the samples.

(*) Permanent address: Belarus State University of Informatics and RadioElectronics - P. Brovka str., 6 Minsk 220013, Belarus.

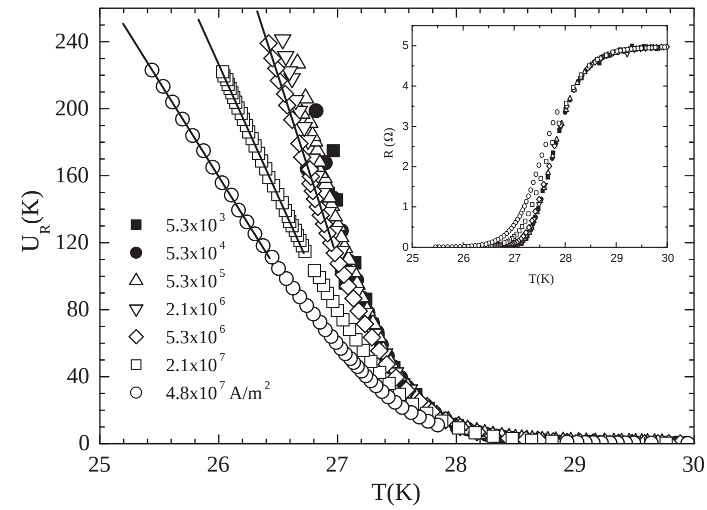

Fig. 1 – The activation energy $U_R(T)$ dependencies, as obtained from the resistive transitions in the inset, using eq. (2), for different J values at $\mu_0 H = 2\,\mathrm{T}$. The solid lines show the linear dependencies of the $U_R(T)$ curves. Inset: resistive transitions at $\mu_0 H = 2\,\mathrm{T}$ and different bias current densities for an *in situ* sputtered MgB_2 thin film.

High-textured MgB_2 films were prepared on R-cut sapphire substrates using a magnetron sputtering technique with subsequent *in situ* annealing in the presence of saturated Mg vapour. Details of the fabrication procedure can be found elsewhere [13]. The critical temperatures of the optimised films were higher than 30 K with the width of the transition (90%–10%) less than 0.5 K. The critical current densities were higher than $10^{10}\,\mathrm{A/m^2}$ at 15 K with an externally applied magnetic field $\mu_0 H = 2\,\mathrm{T}$ [11], confirming the presence of high intergranular current [14] and comparable to the best results for films [15,16]. The resistivity ρ of the films had a metallic signature (*i.e.* ρ decreases linearly with decreasing temperature), indicating no influence of the dielectric grain boundaries. Transport measurements were carried out by a standard d.c. four-probe method. A microbridge geometry was obtained on the films by a usual scribing method [17] using a diamond knife. The final dimensions of the microbridges were typically about $50\,\mu\mathrm{m} \times 350\,\mu\mathrm{m}$. The above procedure did not deteriorate the film superconducting properties. The magnetic field, up to 9 T, was applied perpendicularly to the film surface. The resistivity values of the investigated MgB_2, $\rho \approx 2\,\mathrm{m}\Omega\,\mathrm{cm}$ at 40 K, were higher than those observed for bulk samples [18] and wires [19] probably due to the disorder present in the *in situ* annealed films. On the other hand, the pronounced surface roughness places a large uncertainty in the actual thickness of the samples, which we took, as an upper limit, to be $1\,\mu\mathrm{m}$. Consequently, the calculated values for the sample current density represent a lower limit of the actual current flowing in the samples.

In the inset to fig. 1, the resistive transitions of a MgB_2 thin film are shown at 2 T for different bias current densities in the range from $5.3 \times 10^3\,\mathrm{A/m^2}$ to $4.8 \times 10^7\,\mathrm{A/m^2}$. The broadening of the curves is evident. The influence of thermal effects on this broadening can be ruled out because of the low values of the used bias current densities with respect to the critical current density J_c measured on the samples (around $10^{10}\,\mathrm{A/m^2}$ at 2 T for temperatures in the range from 20 to 26 K), because of its presence only in the low-temperature part of the transition curves (while the onset is not changed) and finally, because *I*-*V* measurements, taken with increasing and decreasing voltages in the range of the used bias currents, did

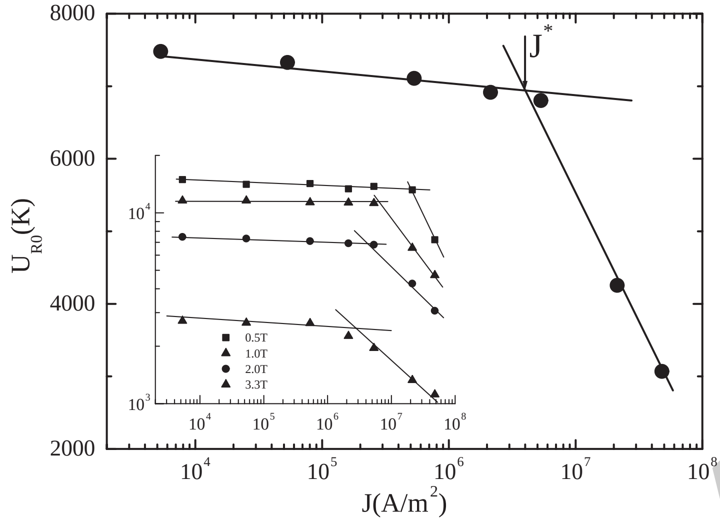

Fig. 2 – The linearly extrapolated zero-temperature activation energy $U_{R0}(J)$-dependence at $\mu_0 H = 2\,\mathrm{T}$, obtained from the data in fig. 1. The solid lines are guides to the eyes. The arrow indicates the position of the crossover current density J^*. Inset: $U_{R0}(J)$ dependencies at different magnetic fields. The lines are guides to the eyes.

not show any sign of hysteresis. Similar broadening, generally observed in the dissipative properties of MgB_2 samples, has been related to the presence of flux creep effects [12, 20–22]. In this case, the resistive curves can be expressed as [23]

$$R(T,H,J) = R_0 \exp\left[-\frac{U_R(T,H,J)}{K_\mathrm{B}T}\right], \tag{1}$$

where R_0 is a coefficient associated to the normal resistance just above the transition R_N, k_B is the Boltzmann constant and U_R is the effective activation energy as obtained from the transport measurements. In order to study the H and J dependencies of U_R it is worth rewriting eq. (1) as

$$U_R(T,H,J) = K_\mathrm{B}T \ln\left[\frac{R_\mathrm{N}}{R(T,H,J)}\right]. \tag{2}$$

The $R(T)$ data in the inset to fig. 1, according to eq. (2), are used to calculate U_R, and are shown in fig. 1. The curves of the U_R values taken at current densities smaller than $1 \times 10^7\,\mathrm{A/m^2}$ are very close to each other, while those related to current bias densitites higher than $1 \times 10^7\,\mathrm{A/m^2}$ are well separated. Nevertheless, in agreement with previous results [22], for all the curves in fig. 1, there is some temperature range, where the $U_R(T)$-dependence is linear, indicating the presence of a well-defined activation energy influencing the vortex dynamics of our samples. To better emphasize the current-dependent behaviour of the U_R values, we have decided to use, as a suitable phenomenological parameter, U_{R0}, the linear extrapolation of the activation energy in the zero-temperature limit. We underline that here U_{R0} is only a useful parameter to compare the different current behaviours observed in fig. 1, without any particular physical meaning. In fig. 2, the obtained $U_{R0}(J)$-dependence at $2\,\mathrm{T}$ is shown using a semilogarithmic scale. The data indicate the presence of a crossover current density J^*, separating two different $U_{R0}(J)$ behaviours. For $J < J^*$, U_{R0} is almost constant, changing slightly between 7400 K and 6900 K (*i.e.* less than 7%), while J is changed over three decades.

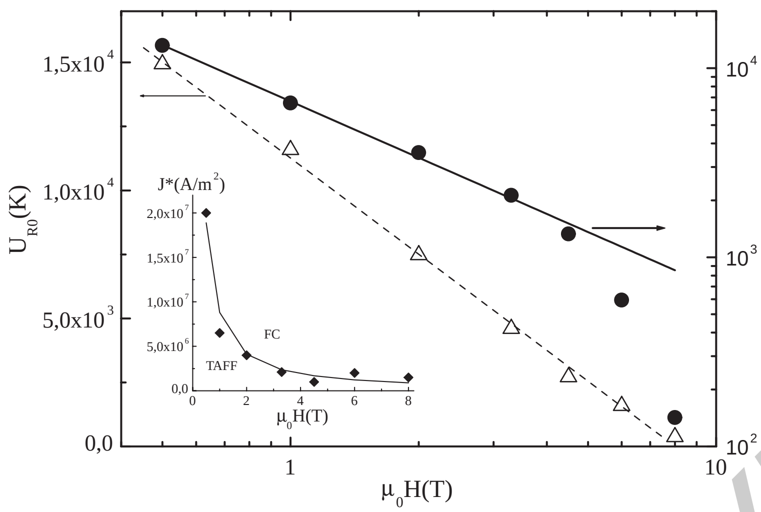

Fig. 3 – The activation energy magnetic-field dependence $U_{R0}(H)$ at $J = 5.3\times10^3$ A/m^2 (left vertical axis). The dashed line is the logarithmic law, $U_{R0}(H) \sim -\ln H$. The $U_{R0}(H)$-dependence at $J = 2.1 \times 10^7$ A/m^2 (right vertical axis). The solid line is the hyperbolic law, $U_{R0}(H) \sim H^{-1}$. Inset: the magnetic-field crossover current density $J^*(H)$-dependence as obtained from the $U_{R0}(J)$ curves at different magnetic fields. The solid line is the best-fit curve to the data according to the law $J^* \sim H^\alpha$ with $\alpha = -1.1$.

For $J > J^*$, the U_{R0} value drops down to 3000 K when the current density is varied within only one decade and the $U_{R0}(J)$-dependence shows a logarithmic behaviour. Notwithstanding the small number of experimental points in this region, this logarithmic dependence has been confirmed also at different magnetic fields, as shown in the inset to fig. 2 for fields from 0.5 to 3.3 T. From the data in the inset, it is also clear that the crossover current J^* depends on the actual external magnetic-field value, and it is therefore possible to identify a curve in the $J(H)$ plane, which separates two different $U(J)$ behaviours. The change in the $U(J)$-dependence could be related to a current-driven transition in the flux dynamics of our MgB_2 thin films. If so, this change in the vortex dynamics should also be reflected in the magnetic-field dependence of the activation energy. In fig. 3, we show the $U_{R0}(H)$-dependence at $J = 5.3\times10^3$ A/m^2 ($J < J^*$), in a semilogarithmic scale (left axis), to point out the logarithmic behaviour of the $U_{R0}(H)$, along with the $U_{R0}(H)$-dependence at $J = 2.1 \times 10^7$ A/m^2 ($J > J^*$), presented in a double logarithmic plot (right axis). The solid line corresponds to a hyperbolic law, $U_{R0} \sim H^{-1}$, which well describes the data up to 5 T. The curve in the $J(H)$ plane, therefore, separates two regions with different vortex dynamics, one resulting in almost constant $U(J)$ behaviours and logarithmic $U(H)$ dependencies ($J < J^*$), the other ($J > J^*$) with logarithmic $U(J)$ curves and hyperbolic $U(H)$ behaviours. At high temperatures, the logarithmic dependence in $U(J)$ ($U(J) \sim -\ln J$) and the hyperbolic behaviour of $U(H)$ ($U(H) \sim H^{-1}$) have been already observed in MgB_2 samples, as well as the linear temperature dependence of U [22]. Here the focus is on the presence of the $J^*(H)$ curve which clearly marks a transition in the vortex dynamics of the system. The $J^*(H)$ curve is shown in the inset to fig. 3.

Our measurements have been performed above the irreversibility line, where the constant $U(J)$-dependence, which corresponds to linear current-voltage characteristics, is generally interpreted in terms of thermally activated flux flow (TAFF) [24]. Moreover, our deduction of finite values of the activation energy in the $J \to 0$ limit, is consistent with the picture of vortices undergoing, for $J < J^*$, the TAFF regime [25], which makes the existence of finite voltage possible also for small transport currents [24, 26] (unlike, for example, the glass state where $U(T, H, J \to 0) \to \infty$ [27]). The logarithmic $U(H)$-dependence, observed below the J^* line in the TAFF regime, can be related [28] to the predominant role of potential pinning energies with an exponential distribution [29] in the limit of small current densities.

The logarithmic $U(J)$ and the hyperbolic $U(H)$ dependencies observed in the region above the $J^*(H)$ line can be interpreted in terms of the FC regime [23]. The $U(H) \sim H^{-1}$ dependence is typical for three-dimensional vortices [23] and usually has been observed, associating it to flux creep effects, in low anisotropy materials, such as $La_{1.86}Sr_{0.14}CuO_4$ [30], $YBa_2Cu_3O_{7-x}$ [31], and bulk MgB_2 [22, 32]. Moreover, the logarithmic $U(J)$-dependence has been also related to the presence of vortex creep regime, where the pinning energy distribution has a strong influence on the vortex dynamics. Indeed, as was previously shown [29], the $U \sim -\ln J$ law can be obtained independently of the pinning spatial shape when the U energy distribution has a large variance, *i.e.* the system is highly disordered. The slightly smaller T_c value (35 K) measured on our thin-film sample, with respect to the bulk value (39 K), and the high values of the resistivity ρ, can be related to structural disorder present in the system.

We propose, therefore, to interpret the $J^*(H)$ curve, shown in the inset to fig. 3, as the line separating into two zones the vortex dynamics of MgB_2 thin films, above the irreversibility line. Below the $J^*(H)$ line, the vortex system is in the thermally activated flux flow regime, while above the line vortices experience flux creep effects. The solid line in the inset to fig. 3 is the best fit to the data obtained with a $J^* \sim H^{-1.1}$ law. At least in the films investigated in this work, the disorder seems to play a very important role in the dissipative properties, in both the zones across the $J^*(H)$ line. The exact nature of this disorder and its detailed influence on the dissipative properties of the system are presently under investigation and will be the issue of future work. Finally, the fast decrease of the U_{R0} values, observed for fields larger than 4 T in fig. 3, could be due to the increase of the vortex-vortex interaction at high magnetic fields which naturally lowers the activation energy.

In conclusion, transport measurements on thin-film microbridges of MgB_2 have been carried out in magnetic fields up to 9 T for various values of the bias current densities, obtaining the current and the magnetic-field dependencies of the activation energy, $U(J)$ and $U(H)$. A crossover current density curve $J^*(H)$ separates the $J(H)$ plane into two regions with different $U(J)$ and $U(H)$ behaviours. At $J < J^*$, the $U(J) \approx$ const and the $U(H)$-dependence is logarithmic, while at $J > J^*$, $U(J) \sim -\ln J$ and the $U(H)$-dependence is hyperbolic up to about 5 T, and then decreases very fast probably because of the increase in the vortex interaction. The crossover current J^* is associated with the TAFF-FC transition. In the TAFF region, the $U(H)$-dependence seems to be influenced by the distribution of the vortices among the strongest pins, which, in their turn, are distributed exponentially. In the FC region the $U(J)$-dependence is logarithmic, which could be also associated with the distribution of pinning energies in a disordered system.

* * *

We thank Prof. R. Vaglio for having provided the *in situ* grown MgB_2 thin films.

REFERENCES

[1] Canfield P. C., Bud'ko S. L. and Finnemore D. K., *Physica C*, **385** (2003) 1.
[2] Bouquet F., Wang Y., Fisher R. A., Hinks D. G., Jorgensen J. D., Junod A. and Phillips N. V., *Europhys. Lett.*, **56** (2001) 856.

[3] Szabó P., Samuely P., Kačmarčík J., Klein T., Marcus J., Fruchart D., Miraglia S., Marcenat C. and Jansen A. G. M., *Phys. Rev. Lett.*, **87** (2001) 137005.
[4] Iavarone M., Karapetov G., Koshelev A. E., Kwok W. K., Crabtree G. W., Hinks D. G., Kang W. N., Choi E.-M., Kim H. J., Kim H.-J. and Lee S. I., *Phys. Rev. Lett.*, **89** (2002) 187002.
[5] Angst M., Puzniak R., Wisniewski A., Jun J., Kazakov S. M., Karpinski J., Roos J. and Keller H., *Phys. Rev. Lett.*, **88** (2002) 167004.
[6] Angst M., Puzniak R., Wisniewski A., Jun J., Kazakov S. M. and Karpinski J., *Phys. Rev. B*, **67** (2003) 012502.
[7] Bud'ko S. L. and Canfield P. C., *Phys. Rev. B*, **65** (2002) 212501.
[8] Dulčič A., Pozek M., Paar D., Choi E.-M., Kim H.-J., Kang W. N. and Lee S.-I., *Phys. Rev. B*, **67** (2003) 020507.
[9] Caplin A. D., Bugoslavsky Y., Cohen L. F., Cowey L., Driscoll J., Moore J. and Perkins G. K., *Supercond. Sci. Technol.*, **16** (2003) 176.
[10] Kunchur M. N., Lee S. I. and Kang W. N., Arxiv: cond-matt/0212108.
[11] Prischepa S. L., Della Rocca M. L., Maritato L., Salvato M., Di Capua R., Maglione M. G. and Vaglio R., *Phys. Rev. B*, **67** (2003) 024512.
[12] Bugoslavsky Y., Perkins G. K., Qi X., Cohen L. F. and Caplin A. D., *Nature*, **410** (2001) 563.
[13] Vaglio R., Maglione M. G. and Di Capua R., *Supercond. Sci. Technol.*, **15** (2002) 1236.
[14] Kawano K., Abell J. S., Kambara M., Hari Babu N. and Cardwell D. A., *Appl. Phys. Lett.*, **79** (2001) 2216.
[15] Moon S. H., Yun J. H., Lee H. N., Kye J. I., Kim H. G., Chung W. and Oh B., *Appl. Phys. Lett.*, **79** (2001) 2429.
[16] Kim H.-J., Kang W. N., Choi E.-M., Kim M.-S., Kim K. H. P. and Lee S.-I., *Phys. Rev. Lett.*, **87** (2001) 087002.
[17] Chiao R. I., Feldman M. J., Ohta H. and Parris P. T., *Rev. Phys. Appl.*, **9** (1974) 183.
[18] Gumbel A., EcKert J., Fuchs G., Nenkov K., Muller K.-H. and Schultz L., *Appl. Phys. Lett.*, **80** (2002) 2725.
[19] Canfield P. C., Finnemore D. K., Bud'ko S. L., Ostenson J. E., Lapertot G., Cunningham C. E. and Petrovic C., *Phys. Rev. Lett.*, **86** (2001) 2423.
[20] Qin M. J., Wang X. L., Lin H. K. and Dou S. X., *Phys. Rev. B*, **65** (2002) 132508.
[21] Thompson J. R., Paranthaman M., Christen D. K., Sorge K. D., Kim H. J. and Ossandon J. G., *Supercond. Sci. Technol.*, **14** (2001) L17.
[22] Yan J. K. F., Lee C. M., Han Y. S., Shen L. J. and Jin X., *Solid State Commun.*, **121** (2002) 317.
[23] Tinkham M., *Phys. Rev. Lett.*, **61** (1988) 1658.
[24] Kes P. H., Aarts J., Van den Berg J., van der Beek C. J. and Mydosh J. A., *Supercond. Sci. Technol.*, **1** (1989) 242.
[25] Prischepa S. L., Vecchione A., Kushnir V. N., Salvato M., Petrov A. Yu., Attanasio C. and Maritato L., *Supercond. Sci. Technol.*, **12** (1999) 533.
[26] Dew-Hughes D., *Cryogenics*, **28** (1988) 674.
[27] Fisher M. P. A., *Phys. Rev. Lett.*, **62** (1989) 1415.
[28] Inui M., Littlewood P. B. and Coppersmith S. N., *Phys. Rev. Lett.*, **63** (1989) 2421.
[29] Kushnir V. N., Coccorese C., Prischepa S. L. and Salvato M., *Physica C*, **275** (1997) 211.
[30] McHenry M. E., Simizu S., Lessure H., Maley M. P., Coulter J. Y., Tanaka I. and Kojima H., *Phys. Rev. B*, **44** (1991) 7614.
[31] Sun J. Z., Char K., Hahn M. R., Geballe T. H. and Kapitulnik A., *Appl. Phys. Lett.*, **54** (1989) 663.
[32] Qin M. J., Wang X. L., Soltanian S., Li A. H., Liu H. K. and Dou S. X., *Phys. Rev. B*, **64** (2001) 060505.