Current-dependent crossover in the flux dynamics of MgB$_2$ thin films

S. L. Prischepa, M. Salvato and L. Maritato
Taking full advantage of the service on Internet, please choose the fastest connection:
http://www.edpsciences.org
http://edpsciences.nao.ac.jp
http://edpsciences-usa.org
http://www.epletters.ch

Editor-in-Chief
Prof. H. Müller-Krumbhaar
IFF Theorie 3 - Forschungszentrum Jülich
D-52425 Jülich - Germany
h.mueller-krumbhaar@fz-juelich.de

Staff Editor: Edith Thomas
Europhysics Letters, European Physical Society, 34 rue M. Seguin, 68060 Mulhouse Cedex, France

Editorial Director: Angela Oleandri

Publishers: EDP Sciences S.A., France - Società Italiana di Fisica, Italy

Europhysics Letter was launched more than fifteen years ago by the European Physical Society, the Société Française de Physique, the Società Italiana di Fisica and the Institute of Physics (UK) and owned now by 17 National Physical Societies/Institutes.

Europhysics Letters aims to publish short papers containing non-trivial new results, ideas, concepts, experimental methods, theoretical treatments, etc. which are of broad interest and importance to one or several sections of the physics community.

Europhysics letters provides a platform for scientists from all over the world to offer their results to an international readership.

Subscription 2004
24 issues - Vol. 65-68 (6 issues per vol.)
ISSN: 0295-5075 - ISSN electronic: 1286-4854

- France & EU
  (VAT included)
  1 678 €
- Rest of the World
  (without VAT)
  1 678 €

Payment:
☐ Check enclosed payable to EDP Sciences
☐ Please send me a pro forma invoice
☐ Credit card:
  ☐ Visa ☐ Eurocard ☐ American Express

Valid until:

Card No: □□□□□□□□□□□□□□□□□□□

☐ Please send me a free sample copy

Institution/Library: ..........................
...........................................

Name: ..........................
Position: ..........................
Address: ..........................
..........................................
..........................................

ZIP-Code: ..........................
City: ..........................
Country: ..........................
E-mail: ..........................

Signature:

Order through your subscription agency or directly to EDP Sciences:
17 av. du Hoggar • B.P. 112 • 91844 Les Ulis Cedex A • France
Tel. 33 (0)1 69 18 75 75 • Fax 33 (0)1 69 86 06 78 • subscribers@edpsciences.org
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)

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, $U(J) \approx \text{const}$, 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 $\mu_0 H \approx 5$ 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 $G_i \approx 10^{-5}$, which measures the importance
of the thermal fluctuations against the condensation energy, flux creep (FC) effects have
been found to strongly influence the dissipative behaviour, especially with increasing exter-
nal 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.
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$^{10}$ A/m$^2$ at 15 K with an externally applied magnetic field $\mu_0 H = 2$ T [11], confirming the presence of high intergranular current [14] and comparable to the best results for films [15,16]. The resistivity $\rho$ of the films had a metallic signature (i.e. $\rho$ 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 $\mu$m $\times$ 350 $\mu$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$_2$, $\rho \approx 2$ m$\Omega$.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 $\mu$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 $5.3 \times 10^3$ A/m$^2$ to $4.8 \times 10^7$ 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 $10^{10}$ 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
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]

$$R(T,H,J) = R_0 \exp \left( \frac{U_R(T,H,J)}{K_B T} \right),$$

(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

$$U_R(T,H,J) = K_B T \ln \left( \frac{R_N}{R(T,H,J)} \right).$$

(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 $1 \times 10^7$ A/m$^2$ are very close to each other, while those related to current bias densities higher than $1 \times 10^7$ 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 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.
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 $J = 5.3 \times 10^3$ 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 $U(T,H,J \rightarrow 0) \rightarrow \infty$ [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$_2$Cu$_3$O$_{7-x}$ [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 (35K) measured on our thin-film sample, with respect to the bulk value (39K), and the high values of the resistivity $\rho$, 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 $U_{R_0}$ 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 $U(J) \approx \text{const}$ 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