Fluxon dynamics by microwave surface resistance measurements in MgB$_2$

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Abstract

Field-induced variations of the microwave surface resistance, $R_s(H)$, have been investigated in high-density ceramic MgB$_2$. At low temperatures, several peculiarities of the $R_s(H)$ curves cannot be justified in the framework of models reported in the literature. We suggest that they are ascribable to the unconventional vortex structure in MgB$_2$, related to the presence of two gaps. On the contrary, the results near $T_c$ can be accounted for by the Coffey and Clem model, with fluxons moving in the flux-flow regime, provided that the anisotropy of the upper critical field is taken into due account.

Key words: MgB$_2$, Microwave surface impedance, fluxon dynamics

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1 Introduction

Since the discovery of superconductivity in the MgB$_2$ compound, several authors have investigated the properties of such superconductor in the presence of magnetic fields. It has been shown that the electric, magnetic and transport properties of MgB$_2$ are strongly affected by the magnetic field [1,2,3,4]. Such enhanced field dependence of the properties of MgB$_2$ has been ascribed

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to the peculiar two-gap structure, with a larger gap, associated with the two-dimensional $\sigma$ band, and a smaller gap, associated with the three-dimensional $\pi$ band, which is rapidly suppressed by the applied magnetic field [5,6,7].

Measurements of the microwave (mw) surface resistance, $R_s$, allow investigating the processes responsible for mw energy losses in superconductors as well as determining specific properties of the samples. It is well known that the mw surface resistance of superconductors in the mixed state depends on the magnetic field through several mechanisms [8,9]. The different vortex states, in the different regions of the H-T plane, determine the temperature and field dependencies of $R_s$. Therefore, measurements of $R_s(H,T)$ may provide important information on the fluxon dynamics in the different regimes of fluxon motion.

It has been shown that mw losses in MgB$_2$ superconductor are strongly affected by the magnetic field in the whole range of temperatures below $T_c$, even for relatively low field values [4,10,11]. In particular, an unusually enhanced field dependence of $R_s$ has been observed at $T \ll T_c$, where pinning effects should hinder the energy losses.

In this paper, we report experimental results of the field-induced variations of the mw surface resistance in high-density ceramic MgB$_2$. Below $T = 0.95T_c$, we have observed a magnetic hysteresis in the $R_s(H)$ curves, whose peculiarities cannot straightforwardly be justified by models reported in the literature. On the contrary, the experimental results obtained near $T_c$ are well accounted for in the framework of the Coffey and Clem model [9], with fluxons moving in the flux-flow regime, provided that the anisotropy of the upper critical field is taken into due account.

2 Experimental

The field-induced variations of $R_s$ have been studied in a bulk ceramic MgB$_2$ sample of approximate dimensions $2 \times 3 \times 0.3$ mm$^3$, with $T_c \approx 39$ K. The sample has been extracted from a high-density pellet (2.4 g/cm$^3$) obtained by reactive infiltration of liquid Mg on a powdered B preform [12]. After the reaction in a sealed stainless steel container, lined with a Nb foil, a thermal treatment has been performed for two hours at $T \approx 900$ °C.

The mw surface resistance has been measured using the cavity perturbation technique. The cavity, of cylindrical shape with golden-plated walls, is tuned in the $TE_{011}$ mode resonant at 9.6 GHz ($Q$-factor $\approx 40,000$ at $T = 4.2$ K). The sample is put in the center of the cavity by a sapphire rod, in the region of maximum mw magnetic field. The cavity is placed between the poles.
of an electromagnet, which generates DC magnetic fields up to \( \approx 10 \) kOe. Two additional coils allow reducing to zero the residual field and working at low magnetic fields. The quality factor of the cavity has been measured by an hp-8719D Network Analyzer. \( R_s \) has been investigated as a function of the DC magnetic field, \( H_0 \), in the range \( 0 \div 10 \) kOe, at fixed values of temperature. Before each measurement was performed, the sample was zero-field cooled (ZFC) to the desired value of temperature; the external field was then increased up to 10 kOe and successively decreased to zero, at constant temperature. The sample and field geometry is shown in Fig.1 a); in this geometry the mw current induces a tilt motion of all the fluxons present in the sample, as shown in Fig.1 b).

Fig.2 shows the field dependence of \( R_s \), normalized to the normal-state surface resistance, \( R_n \), measured at \( T = 40 \) K, for different values of the temperature. Open and solid symbols refer to results obtained on increasing and decreasing \( H_0 \), respectively. As one can see, up to \( \sim 4 \) K below \( T_c \) the \( R_s(H) \) curves show a magnetic hysteresis. The inset shows the temperature dependence of the height of the hysteresis loop at \( H_0 = 0 \), \( \Delta R_s(0)/R_n \), i.e. the variation of \( R_s/R_n \) after a complete cycle of the DC magnetic field from 0 to 10 kOe and back. On increasing the temperature up to \( T \approx 34 \) K, \( \Delta R_s(0)/R_n \) takes a constant value; on further increasing the temperature it quickly decreases; the hysteretic behavior vanishes at temperatures very close to \( T_c \).

Both the increasing and decreasing-field branches of the \( R_s(H) \) curves show a plateau in the field ranges \( 0 \div H_p \) and \( 0 \div H^* \), respectively. Since the sample was ZFC, \( H_p \) marks the first-penetration field. Fig 3 a) shows \( H_p \) as function of temperature; the line has been obtained by fitting the experimental data with the law \( H_p(T) = H_p(0)[1 - (T/T_c)^\beta] \); we have obtained, as best-fit parameters, \( H_p(0) = 390 \pm 20 \) Oe and \( \beta = 2.4 \pm 0.2 \). The \( \beta \) value gives a temperature dependence of \( H_p \) consistent with that of \( H_{c1}(T) \). \( H_p(0) \) is slightly larger than the values of \( H_{c1}(0) \) reported in the literature for MgB\(_2\), suggesting that in our sample surface-barrier effects are weak.

Fig.3 b) shows the temperature dependence of \( H^* \), though the meaning of this characteristic parameter is not clear, one can note that its temperature
Fig. 2. Magnetic-field dependence of $R_s$ at different values of temperature. Open and solid symbols refer to measurements performed at increasing and decreasing field, respectively. The inset shows the height of the hysteresis loop at $H_0 = 0$ as a function of temperature.

dependence is very similar to that of $H_p$.

3 Discussion

Microwave losses induced by DC magnetic fields in superconductors in the mixed state are proportional to the complex penetration depth of the mw field, $\tilde{\lambda}$; they are influenced by the fluxon motion and the very presence of vortices which bring along normal fluid in their core [9]. $\tilde{\lambda}$ can be expressed in terms of the normal-fluid density, flux-flow resistivity and $\nu/\nu_0$ ratio, where $\nu$ is the working frequency and $\nu_0 = \alpha_L/\eta$ the depinning frequency, with $\alpha_L$ the Labush parameter and $\eta$ the viscous-drag coefficient. For $\nu \gg \nu_0$ the
induced mw current makes fluxons moving in the flux-flow regime. Otherwise, the fluxon motion is ruled by the strength of the restoring-pinning forces.

Our results show that for $T < 35$ K the $R_s(H)$ curves exhibit an hysteretic behavior, suggesting that pinning effects are important in this range of temperatures. On the contrary, for $T > 35$ K the hysteresis vanishes and fluxons should move in the flux-flow regime. Actually, the results near $T_c$ can be accounted for by using the Coffey and Clem theory [9], with fluxons moving in the flux-flow regime, provided that the anisotropy of the upper critical field is taken into due account. Following the same procedure of Ref.[4], based on the assumption that the anisotropic Ginzburg-Landau theory is valid for MgB$_2$ in this range of temperatures, we have fitted the experimental data by taking the anisotropy factor, $\gamma$, as fitting parameter. The best-fit curves, along with the experimental data, are shown in Fig.4. For all the curves, the best-fit value of the anisotropy factor is $\gamma = 3$, showing that in our sample the anisotropy of $H_{c2}$ is constant in a range of temperatures of about 3 K below $T_c$.

The hysteresis of the $R_s(H)$ curves, observed for $T < 35$ K, should be re-
lated to the different value of the induction field at increasing and decreasing fields. Both the normal fluid density and the flux-flow resistivity depend on the number of fluxons moving under the action of the mw current. In the field geometry we used the mw current induces a tilt motion of all the fluxons present in the sample (see Fig.1). So, the hysteresis of $R_s(H)$ should be directly related to the hysteretic behavior of the magnetization curve due to pinning effects. However, several anomalies can be highlighted in the $R_s(H)$ curves at low temperatures. Firstly, from Fig.2 one can see that an unusually enhanced field variation of $R_s$ is observed, even at the lowest temperatures; a magnetic field of 10 kOe induces an $R_s$ variation of about 1/3 of the normal-state value. We suggest that such enhanced field-induced energy losses are ascribable to the effects of the two-gap structure of MgB$_2$. Indeed, it has been shown that the structure of vortices in MgB$_2$ is characterized by two coherence lengths, associated with each band [6,13]. On increasing the applied field, the giant cores start to overlap at field values much smaller than $H_{c2}$. Therefore, modest fields can suppress superconductivity between the vortices, resulting in an enhancement of the normal-fluid density [6,7,13]. Furthermore, this particular vortex structure can modify the interaction among vortices and pinning centers, giving rise to an unconventional shape of the pinning potential well.

Another anomaly concerns the shape of the decreasing-field branch of the $R_s(H)$ hysteresis loop. By supposing fluxons in the critical state, after the external field starts decreasing the variation of $B(H)$ should be initially slow and then faster, no matter the field dependence of the critical current. So, a downward curvature of the decreasing-field branch of the $R_s(H)$ curve is expected, at variance with our results. The origin of this anomalous behavior, as well as the presence of the wide plateau in the decreasing-field $R_s(H)$ curves, is not yet understood and needs further investigation.

In conclusion, we have reported a detailed study of the field-induced variations of the mw surface resistance in high-density ceramic MgB$_2$. An unusual behavior of the $R_s(H)$ curves has been highlighted at low temperatures, which cannot be explained in the framework of models reported in the literature. We suggest that it is ascribable to the unconventional vortex structure related to the presence of the two gaps. On the contrary, the results obtained at temperatures close to $T_c$ have been accounted for in the framework of the Coffey and Clem model, with fluxons moving in the flux-flow regime, by taking into account the anisotropy of upper critical field.

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