Fluxon dynamics in Li–Al codoped MgB$_2$ by microwave surface resistance measurements

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A R T I C L E   I N F O

A B S T R A C T

The magnetic-field-induced variations of the microwave surface resistance, R_s, have been investigated in ceramic Mg$_{1-x}$(LiAl)$_x$B$_2$, with x in the range $0.1-0.4$. The measurements have been performed on increasing and decreasing the DC magnetic field, H_0, at fixed temperatures. At low temperatures, we have observed a magnetic hysteresis in the $R_s(H_0)$ curves in all the investigated samples. On increasing the temperature, the range of H_0 in which the hysteretic behavior is visible shrinks; however, in the sample with $x = 0.1$ it is present up to temperatures close to T_c. We show that the field dependence of R_s can be quantitatively justified taking into account the critical-state effects on the fluxon lattice only in the sample with $x = 0.4$. On the contrary, in the samples with $x < 0.4$ the hysteresis exhibits an unusual shape, similar to that observed in others two-gap MgB$_2$ samples, which cannot be justified in the framework of the critical-state models.

1. Introduction

It has already been shown that the in-field microwave (mw) response of two-gap MgB$_2$ superconductor cannot be accounted for by standard models for fluxon dynamics [1–3]. The anomalies have been ascribed to the unusual structure of fluxons, related to the different field dependence of the two superconducting gaps [4,5]. Support to this hypothesis has been given from investigation of a strongly neutron-irradiated MgB$_2$ sample [6], in which the two gaps merged into a single value, and in a two-gap sample only at applied magnetic fields higher than the field at which the smaller gap is almost suppressed [7] (i.e. when fluxons assume a more conventional shape).

According to the theory of multi-band superconductivity, the inclusion of defects, by chemical substitution or irradiation, would increase the inter-band scattering and, consequently, change the relative magnitude of the two gaps. Investigation carried out in neutron-irradiated samples has shown that high-level irradiation produces the merging of the two gaps [8,9]. Recently, samples of Mg$_{1-x}$(LiAl)$_x$B$_2$, with x in the range $0.1-0.4$, have been investigated by point-contact Andreev-reflection spectroscopy [10]. A clear evidence has been given that the samples with $x = 0.1$ and $x = 0.2$ have a typical two gap structure, while in the sample with $x = 0.4$ the two gaps merge into a single value. On the contrary, in the sample with $x = 0.3$ one or two gaps are apparently

observed depending on the local critical temperature of the junction. In this paper, we report results of the magnetic-field dependence of the mw surface resistance, R_s, in the same samples investigated in Ref. [10]. We have found that only the results obtained in the sample with $x = 0.4$ can be accounted for by using a model of fluxon dynamics in single-gap superconductors. In the other samples, we have observed a magnetic hysteresis of unusual shape, similar to that observed in other two-gap MgB$_2$ samples, which cannot be justified in the framework of the critical-state models. Our results confirm that mw measurements may discriminate the gap structure of MgB$_2$ samples.

2. Experimental apparatus and samples

The mw surface resistance has been investigated in ceramic samples of Mg$_{1-x}$(LiAl)$_x$B$_2$, with $x = 0.1-0.4$, in the range of temperatures $3-40$ K and DC magnetic fields up to 1 T. The procedure for the preparation of the samples and their properties are reported in Refs. [10,11]. It is worth remarking that structural characterization by neutron and X-ray diffraction has highlighted that Li enters the MgB$_2$ structure in an amount less than the nominal one [11]; in particular, the correct stoichiometry is Mg$_{1-x}$(Al$_\alpha$Li$_{1-\alpha}$)$_x$B$_2$, with $\alpha \sim 2/3$. The measured T_c of the samples decreases with x, from 36 K down to 20 K, however it depends on the used method of measure; the values of the transition width increase with x from 1.5 K up to 4.4 K.

The mw surface resistance has been measured by the cavity-perturbation technique. A copper cavity, of cylindrical shape with

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golden-plated walls, is tuned in the TE_{011} mode resonating at 9.6 GHz; the sample is located in the center of the cavity, where the mw magnetic field is maximum. The cavity is placed between the poles of an electromagnet which generates DC magnetic fields up to $\mu_0 H_0 = 1$ T. Two additional coils, independently fed, allow compensating the residual field and working at low magnetic fields. Details of the experimental apparatus and the field geometry are reported in Ref. [3]. In all the measurements, H_0 is perpendicular to the mw magnetic field, H_ω. This implies that, when the sample is in the mixed state, the induced mw current causes a tilt motion of the vortex lattice [12]. In this field geometry, the effects of the critical state of the fluxon lattice in the field dependence of R_s are particular enhanced, because one detects the response of the whole fluxon lattice, and a magnetic hysteresis is expected [13,14].

3. Experimental results and discussion

Fig. 1 shows R_s, normalized to its normal-state value, R_n, as a function of the temperature for the samples with $x = 0.1$, $x = 0.3$, and $x = 0.4$ at $H_0 = 0$. On increasing the LiAl content the transition broadens and shifts toward lower temperatures. Because of the wide transition and the large uncertainty of the values reported in the literature for T_c, in this paper we use for T_c the values obtained by the method shown in the figure, which gives $T_c \approx 33.1 \pm 0.2$ K for $x = 0.1$, $T_c \approx 20.9 \pm 0.2$ K for $x = 0.3$ and $T_c \approx 20.2 \pm 0.5$ K for $x = 0.4$.

The field-induced variations of R_s have been measured at different temperatures. For each measurement, the sample was ZFC down to the desired temperature; the DC magnetic field was increased from 0 up to 1 T and, successively, decreased down to zero. Fig. 2 shows the field-induced variations of R_s, obtained at $T/T_c \approx 0.2$. $\Delta R_s(H_0) \equiv R_s(H_0, T) - R_{res}$, where R_{res} is the residual mw surface resistance at $T = 3$ K and $H_0 = 0$; moreover, the data are normalized to the maximum variation, $\Delta R_s^{max} \equiv R_n - R_{res}$. The insets show the curves in a logarithmic scale to better highlight the low-field behavior; the arrow in the increasing-field branch identifies the first-penetration field of fluxons, H_p; the arrow in the decreasing-field branch indicates a characteristic field, H', below which R_s does not change anymore.

In all the samples, the $R_s(H_0)$ curve exhibits a hysteresis, which is ascribable to the different magnetic induction, B, at increasing and decreasing H_0, due to the critical state of the vortex lattice [14]; however, some differences have to be remarked. By comparing the decreasing-field branch of the $R_s(H_0)$ curves of the samples with $x = 0.1$ and $x = 0.4$, one can see that, for $x = 0.4$, R_s monoton-
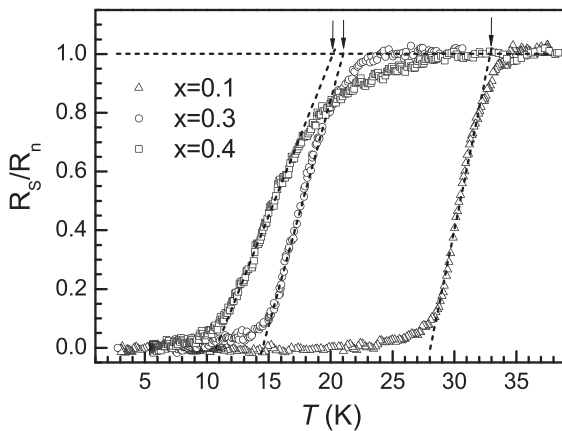

Fig. 2. Field-induced variations of R_s at $T/T_c \approx 0.2$, obtained for $Mg_{1-x}(LiAl)_x B_2$, with different LiAl content. The insets show the curves in a logarithmic scale.

ically decreases down to field values comparable with H_p; this behavior is expected and it is related to the monotonic decrease of B when H_0 is decreased from the maximum value reached down to H_p. On the contrary, for $x = 0.1$, the decreasing-field branch of the $R_s(H_0)$ curve exhibits a plateau starting from $\mu_0 H_0 \approx 0.2$ T, although this value is about 10 times larger than H_p. We wish to remark that we have observed a similar behavior in all the two-gap MgB_2 samples we have investigated [15]. The presence of this plateau cannot be justified in the framework of the critical-state models, because it should indicate that the trapped flux does not change anymore on decreasing the applied field below 0.2 T.

In the sample with $x = 0.3$, a plateau in the decreasing-field branch of the $R_s(H_0)$ curve is also present, but in a field range smaller than that characterizing the decreasing-field branch of Fig. 2a. According to the results of Ref. [10], it could be due to the fact that the LiAl content is not homogenously distributed over the sample; consequently, the sample contains regions with characteristic two-gap superconductivity and regions at single gap.

In Refs. [13,14], we have investigated the effects of the critical state of the fluxon lattice on $R_s(H_0)$ and have elaborated a model, in the framework of the Coffey and Clem theory [16], which quantitatively describes the hysteretic behavior of $R_s(H_0)$. The model has been elaborated considering that, because of the non uniform distribution of B, different regions of the sample contribute differently to the field-induced energy losses. So, in order to calculate $R_s(H_0)$, one has to determine the B profile inside the sample, related

Fig. 1. Temperature dependence of the mw surface resistance (R_n is the normal-state value), obtained for $Mg_{1-x}(LiAl)_x B_2$, with different LiAl content, at $H_0 = 0$. It is shown the procedure followed to determine T_c.
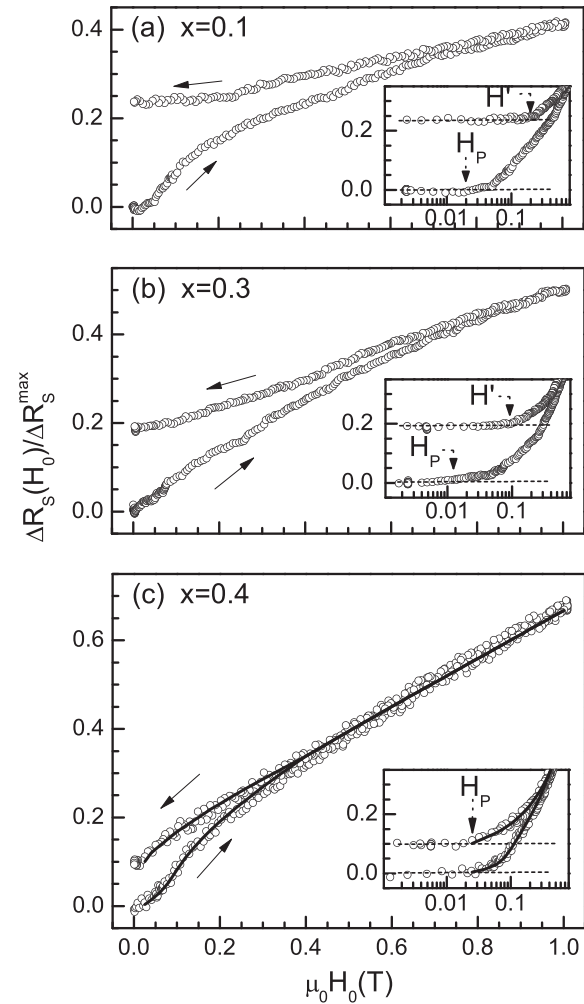
to the field dependence of the critical current density, $J_c(B)$, and calculate a proper averaged value of $R_s(B)$ over the whole sample. From this model, it is expected that the shape of the hysteresis is strongly related to that of the magnetization curve, giving rise to a higher value of R_s at decreasing fields than at increasing fields and a monotonic decrease of R_s when the field is decreased from the maximum value reached down to H_p. The results obtained in the sample with $x = 0.4$ have been analyzed using just this model [14]. The parameters necessary to fit the data are the upper critical field, H_{c2}, $J_c(B)$, the depinning frequency [17], ω_0, and its field dependence. The line in Fig. 2 is the best-fit curve; it has been obtained using $\mu_0 H_{c2} = 1.6$ T; $J_c(B) = J_{c0}(1 - \beta B)$, with $J_{c0} = 9 \times 10^7$ A/m^2 and $\beta = 2.5$ T^{-1}; $\omega_0(B) = \omega_{00}(1 - \gamma B)$, with $\omega_{00} = 6.2$ GHz and $\gamma = 0.625$ T^{-1}.

In Fig. 3 we show a comparison among the $R_s(H_0)$ curves obtained in the different samples at $T/T_c \approx 0.75$ (open symbols); one more curve at $T/T_c \approx 0.94$ is shown in panel (a) for $x = 0.1$ (full symbols). Comparing the curves obtained for different x at $T/T_c \approx 0.75$, one can see that in the sample with $x = 0.4$ no hysteresis is detectable, most likely because of the weakness of the pinning at this temperature. In the other samples, the hysteresis with the characteristic plateau is still present, even if it is visible in a restricted field range. The curve represented in panel (a) by full squares shows that in the sample with $x = 0.1$ the hysteresis is present also at $T/T_c \approx 0.94$, but it manifests itself only through the presence of the plateau below $\mu_0 H_0 \approx 0.05$ T.
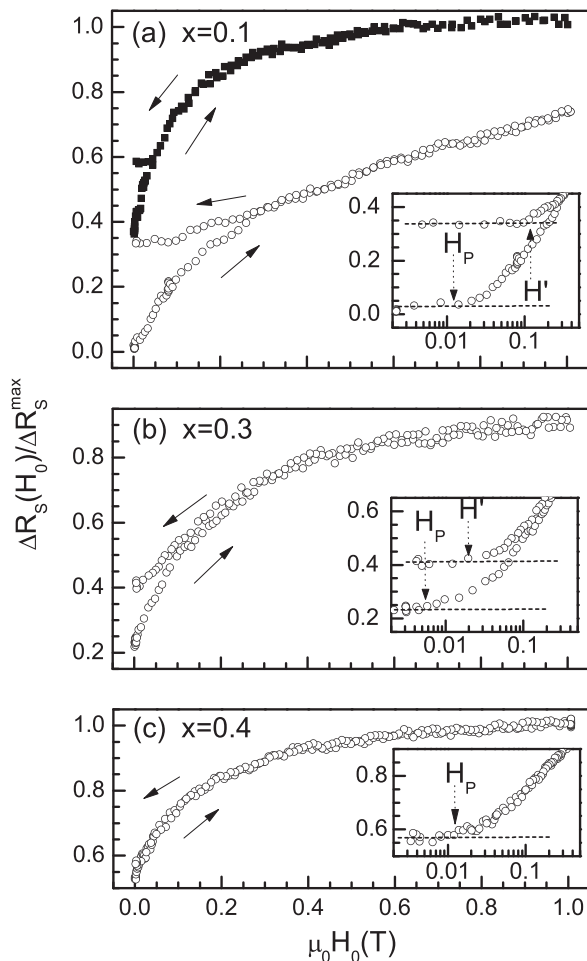
A detailed investigation of $R_s(H_0)$ of the samples with $x = 0.1$ and $x = 0.3$ at temperatures near T_c has shown that for $x = 0.1$ the hysteresis is detectable up to $T/T_c \approx 0.96$; moreover, for $T/T_c \gtrsim 0.87$ it manifests itself only through the presence of the plateau. For $x = 0.3$, the hysteresis disappears at $T/T_c \approx 0.86$. We have also measured the field-induced variations of R_s in a sample with $x = 0.2$; results not here reported have shown a magnetic behavior similar to that obtained for $x = 0.1$, i.e. plateau in the decreasing-field branch of the $R_s(H_0)$ curve and hysteresis visible up to temperatures close to T_c.

The results obtained in the sample with $x = 0.4$ can be fully justified for any temperature using the same model we have used for $T/T_c = 0.2$ (Fig. 2c). However, near T_c in order to fit the data it is necessary to use a distribution function of T_c, increasing the number of fitting parameters. For this reason, we have not reported in Fig. 3c the best-fit curve.

In Ref. [7] we have investigated $R_s(H_0)$ in a two-gap MgB$_2$ sample in the range of fields at which the superconductivity coming from the π band is almost suppressed. In this region ($H_0 \geqslant H_{c2}^\pi$), one expects that the flux lines assume a "conventional" structure and that all the charge carriers coming from the π band are quasi-particles. On this hypothesis, we have elaborated a model that quantitatively describes the field dependence of R_s for $H_0 \geqslant H_{c2}^\pi$. By fitting the data, we have shown that, at least in the temperature range in which the hysteresis manifests itself only through the presence of the plateau, the values of $H_{c2}^\pi(T)$ coincide with the values of H_0 at which the plateau in the decreasing-field branch of $R_s(H_0)$ starts. The result we obtained in [7] allows to determine the temperature dependence of H_{c2}^π at temperatures near T_c. By applying the same arguments of Ref. [7] to the results obtained in the sample with $x = 0.1$, we have deduced a linear dependence of $H_{c2}^\pi(T)$ for $T \geqslant 29$ K, which is well described by the law $H_{c2}^\pi(T) = (0.57 - 0.017\ T)$ T.

4. Conclusion

We have measured the magnetic-field-induced variations of the mw surface resistance in ceramic samples of Mg$_{1-x}$(LiAl)$_x$B$_2$, with $x = 0.1$–0.4. At low temperatures, we have detected a magnetic hysteresis in all the investigated samples, but only that observed in the sample with $x = 0.4$ can be justified in the framework of the standard theory of fluxon dynamics, provided that one considers the distribution of the magnetic induction inside the sample due to the critical state of the fluxon lattice. In the other samples, the decreasing-field branch of the $R_s(H_0)$ curve exhibits a plateau from H_0 much larger than the fluxon-first-penetration field down to zero, which cannot be explained in the framework of critical-state models. It has been already shown that this characteristic of the decreasing-field branch of the $R_s(H_0)$ curve is peculiar of the two-gap MgB$_2$ samples and confirms that in the samples with $x < 0.4$ the two gaps have distinct values. On the contrary, the fact that the sample with $x = 0.4$ have shown a $R_s(H_0)$ curve compatible with the results expected from standard models for fluxon dynamics is consistent with the merging of the two superconducting gaps into a single value, observed in this sample by point-contact Andreev-reflection measurements. Our results confirm that by measuring the field-induced variations of the mw resistance, one may discriminate the gap structure of MgB$_2$ samples.

Acknowledgements

Fig. 3. Field-induced variations of R_s for the Mg$_{1-x}$(LiAl)$_x$B$_2$ samples at temperature near T_c. Open symbols refer to results obtained at $T/T_c \approx 0.75$; full symbols in panel (a) are the results obtained at $T/T_c \approx 0.94$.

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