Directional point-contact spectroscopy of MgB_2 single crystals in magnetic fields: two-band superconductivity and critical fields

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Abstract

The results of the first directional point-contact measurements in MgB_2 single crystals, in the presence of magnetic fields up to 9 T either parallel or perpendicular to the *ab* planes, are presented. By applying suitable magnetic fields, we separated the partial contributions of the σ and π bands to the total Andreev-reflection conductance. Their fit with the BTK model allowed a very accurate determination of the temperature dependency of the gaps (Δ_σ and Δ_π), that resulted in close agreement with the predictions of the two-band models for MgB_2. We also obtained, for the first time with point-contact spectroscopy, the temperature dependence of the (anisotropic) upper critical field of the σ band and of the (isotropic) upper critical field of the π band.

Key words: point-contact spectroscopy; magnesium diboride; critical fields

Point-contact spectroscopy (PCS) has proved particularly useful in investigating the two-band system MgB_2 [1,2], since it allows measuring both the σ- and π-band gaps at the same time. In this paper we show how this technique, combined with the use of magnetic fields and applied to MgB_2 single crystals, has allowed us to measure with the greatest accuracy the temperature dependence of the two gaps (Δ_π and Δ_σ), and of the upper critical fields of the two bands.

The high-quality, plate-like single crystals we used for our measurements were produced at ETH (Zurich) by using the growth technique described elsewhere[3]. The point contacts, that resulted always in the ballistic regime, were made by using either a small spot of silver conductive paint or a small piece of indium placed on the upper flat surface of the crystals or on their side (so as to inject the current mainly parallel or perpendicular to the *c* axis, respectively). A typical conductance curve of a *c*-axis contact, measured at $T = 4.6$ K and normalized to the normal-state conductance, is reported in Fig.1 (circles). It clearly shows the typical features due to Andreev reflection at the normal metal-superconductor interface, with conductance maxima at $V \approx \pm 3.5$ mV and a smooth shoulder at $V \approx \pm 7.2$ mV, clearly related to Δ_π and Δ_σ, respectively. The solid line superimposed to the experimental data is the best-fitting curve obtained with the BTK model generalized to the case of two bands, i.e. by expressing the total normalized conductance as $\sigma = w_\pi \sigma_\pi + (1 - w_\pi)\sigma_\sigma$, where σ_π and σ_σ are the partial normalized conductances of the two bands and w_π is the weight of the π band, that depends on the angle ϕ between the injected current and the *ab* planes [2]. Due to the large number of free fitting parameters (the gaps Δ_π and Δ_σ, the barrier parameters Z_π and Z_σ, the broadening parameters Γ_π and Γ_σ plus the weight w_π), this fitting procedure gives a rather large uncertainty on the gap values. Reducing this uncertainty is however possible by applying a suitable magnetic

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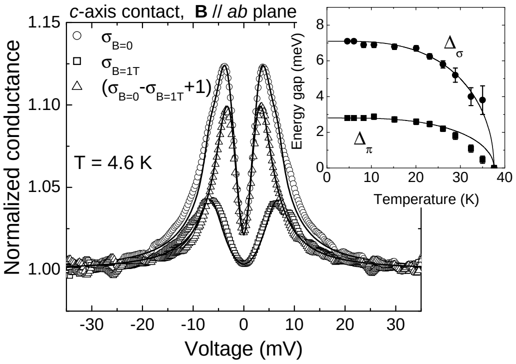

Fig. 1. Normalized conductance curve of a *c*-axis contact, with no magnetic field (circles) and in a magnetic field of 1 T parallel to the *ab*-plane (squares). Triangles: difference between the previous two curves (vertically shifted by 1). Solid lines are the best-fitting BTK curves. Inset: temperature dependence of Δ_σ and Δ_π (symbols) compared to BCS-like curves.

field (i.e. $B \simeq 1$ T at 4.6 K) that completely destroys the superconductivity in the π band without affecting the σ band [4]. The resulting normalized conductance curve (squares in Fig.1) can be simply represented as $\sigma = w_\pi + (1 - w_\pi)\sigma_\sigma$ and can thus be fitted with the standard BTK model, with only three fitting parameters (plus w_π). The best-fit curve reported in Fig.1 was obtained with $w_\pi = 0.98$, Δ_σ=7.09 meV (in very good agreement with the prediction of the two-band model [1,2]), Z_σ=0.6, and Γ_σ=1.7 meV. To get the values of the corresponding quantities relevant to the π band, we subtracted the curve measured in 1 T from that measured in zero field. The resulting curve is reported, shifted by 1, in Fig.1 (triangles). It was fitted with a function of the form $\sigma = w_\pi(\sigma_\pi - 1)$ where w_π is kept equal to 0.98. The resulting best-fit parameters are: Δ_π=2.8 meV (very close to the theoretical value [1,2]), Z_π=0.6, and Γ_π=2.0 meV. By using the same approach we were able to determine the complete temperature dependence of the two gaps, Δ_π and Δ_σ, with unprecedented accuracy [4]. The results are reported in the inset of Fig.1 (symbols) together with the BCS-like curves with gap ratio $2\Delta/k_\mathrm{B}T_\mathrm{c}$ equal to 1.73 and 4.38, respectively. The comparison shows that, at T>25 K, Δ_π is lower than the BCS value, as predicted by the two-band model [1,2].

An example of the effect of the magnetic field on the conductance curves of a point contact (in particular, an *ab*-plane In/MgB$_2$ junction) is reported in the inset of Fig.2. The magnetic field that destroys the superconductivity in the π band, but leaves Δ_σ practically unchanged, is of course the upper critical field of the π band, $B^\pi_{\mathrm{c}2}$. In agreement with the isotropic character of the π bands, we found that $B^\pi_{\mathrm{c}2}$ is independent of the direction of the magnetic field [5]. Its temperature dependence is reported in the main panel of Fig. 2 (solid triangles). The same figure also reports the values of the upper critical field of the σ band, that instead depends on whether $\mathbf{B}\|c$ or $\mathbf{B}\|ab$. For both directions and at $T \gtrsim 0.8T_\mathrm{c}$ the measured critical fields agree rather well with those given by bulk-sensitive techniques such as torque magnetometry (TM) [6], thermal conductivity (TC) [7] and specific heat (SH) [8]. At lower T our fields $B^\sigma_{\mathrm{c}2\|\mathrm{c}}$ and $B^\sigma_{\mathrm{c}2\|\mathrm{ab}}$ are greater than those determined by TM, TC and SH, but lower than the fields which mark the onset of the resistive transition (see upper limit of the shaded region in Fig.2), recently identified with the critical field $B_{\mathrm{c}3}$ [8]. Even if PCS is a surface-sensitive technique, this behavior cannot be simply due to surface nucleation of superconductivity at a field B_0 ($B_{\mathrm{c}2}$<B_0<$B_{\mathrm{c}3}$) because the measured magnetoresistivity of In electrode is always much lower than that of MgB$_2$ crystals [9]. The present results might thus suggest the occurrence of some intrinsic effects, maybe related to slight modifications of the superconducting properties at the MgB$_2$ surface.

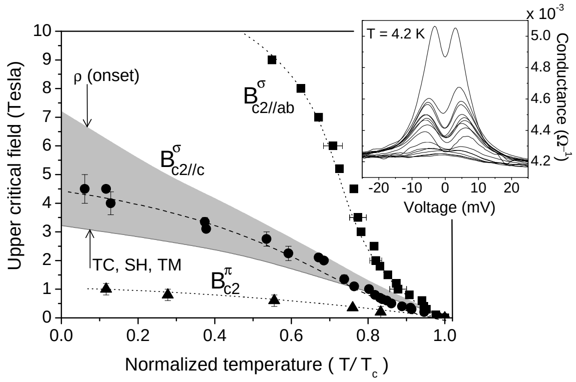

Fig. 2. Upper critical fields $B^\sigma_{c2\|ab}$ (squares), $B^\sigma_{c2\|c}$ (circles) and B^π_{c2} (triangles) vs. temperature. The shaded region is upper-bounded by the values of $B^\sigma_{c2\|c}$ given by the onset of the resistive transition [8] and lower-bounded by those given by thermal conductivity (TC) [7], torque magnetometry (TM) [6], and specific heat (SH) measurements [8]. Dotted lines are only guides to the eye. Inset: conductance curves of a *ab*-plane In/MgB$_2$ junction at 4.2 K in a magnetic field of increasing intensity (up to 7 T) parallel to the *c* axis.

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