Excess current in point contacts on two-band superconductor MgB$_2$ in magnetic field

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A series of $I(V)$ characteristics and bias-dependent differential resistances $dV/dI(V)$ of the point contacts made of the single crystal of two-band superconductor MgB$_2$ were measured in magnetic fields up to 9 T. The magnetic field dependences of the excess current in the $I(V)$ curves were obtained and analyzed using Koshelev and Golubov’s [Phys. Rev. Lett. 90, 177002 (2003)] theoretical results for the mixed state of a dirty two-band superconductor. Introducing a simple model for the excess current in the point contact in the mixed state, our data can be qualitatively described using the theoretical magnetic field dependence of the superconducting order parameter of the $\sigma$ and $\pi$-bands and the averaged electronic density of states in MgB$_2$.

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I. INTRODUCTION

MgB$_2$ has attracted considerable attention due to its high $T_c$ ($\approx$40 K) which is due to specific multi-band electronic structure (see Ref. and Refs. therein). Here superconductivity develops in two-dimensional cylindrical sheets of the Fermi surface constituted from the $\sigma$-band and three-dimensional tubular Fermi surface from the $\pi$-band. The commonly accepted explanation for high-$T_c$ superconductivity in MgB$_2$ is connected with the strong interaction between the charge carriers and the $E_{2g}$ phonon mode caused by the antiparallel vibrations of the atoms in the honeycomb-like boron planes. The superconducting order parameter is distributed over the Fermi surface of MgB$_2$, being $\Delta_\sigma \approx 7$ meV for the $\sigma$-band and $\Delta_\pi \approx 2$ meV for the $\pi$-band. The different properties of the $\sigma$ and $\pi$ bands with different anisotropies result in very peculiar and interesting physical characteristics of MgB$_2$ both in the normal and especially in the superconducting state.

Point-contact (PC) spectroscopy is one of the straightforward methods which has proved the existence the double-gap superconductivity in MgB$_2$ (see, e.g., Refs. and ). Although much was done to understand the remarkable superconducting state in this diboride, some issues should be clarified, such as the behavior of the superconducting gaps in the magnetic field and the rapid depression of the superconducting features of the $\pi$-band in the PC conductivity by a moderate field of about 1 T. In this study we carried out PC measurements both of the order parameter and the excess current versus the magnetic field in MgB$_2$ and analyzed them using the theory for the mixed state of a dirty two-band superconductor.

II. SAMPLES AND MEASUREMENTS

Our experiments were carried out on the MgB$_2$ single-crystal samples investigated earlier in Refs. and . Their properties are described elsewhere. The crystals were small thin plates (flakes) of a sub-millimeter size. They were glued with silver epoxy to the sample holder at one of their side faces. The noble metal counter electrode was brought into a gentle touch with the opposite side face of the crystal in liquid helium. Thus we tried to make a contact mainly along the $ab$ plane, for which both the $\sigma$ and $\pi$-band superconducting features should be present in the PC characteristics. The magnetic field was applied along the $c$-axis.

The $I(V)$ characteristic and the differential resistance $dV/dI(V)$ were recorded through sweeping DC current $I$ on which small AC current $i$ was superimposed and through measuring the alternating voltage $V_1 \propto dV/dI(V)$ using the standard lock-in technique.

III. EXPERIMENTAL RESULTS

First we evaluated the characteristic length scales important for this study. The contact size for the typical resistance of $10 \Omega$ is estimated by the Sharvin formula $d \sim \sqrt{\rho l/R}$ ($d \approx 7$ nm in Ref. and ) irrespectively of the crystallographic directions. For a dirty constrictive (with a very short mean free path) the use of the Maxwell formula $d \sim \rho/\Delta R$ results in $d$ about 0.7 nm and 2.6 nm (see Ref. and ) for the $ab$ plane and $c$ direction, respectively. Thus, the contact size can be of the order of magnitude or smaller than the elastic electron mean free path ($l_\text{ab} = 24$ nm, $l_c = 6$ nm, according to Ref. and ), which means that theoretically we can approach the ballistic (spectroscopic) regime. In practice the spectroscopic regime is confirmed by observation of the characteristic Andreev-reflection features in $dV/dI$ in the su-
perconducting state.

The measurements of the superconducting energy gap in MgB$_2$ by means of the Andreev reflection demonstrate two sets of the energy-gap minima in the differential resistance $dV/dI$ at $\pm 2.4 \pm 0.1$ and $\pm 7.1 \pm 0.4$ meV, respectively; their distribution corresponds to the theoretical prediction. The $dV/dI$ curves can be well fitted by the known BTK equations (with the suitable $\Gamma$ parameter) for two conducting channels with the appropriate weight factors $w_{\pm} \approx 0.7$. The contribution of the large gap to the double-gap spectra $w_0$ is the largest along the $ab$ plane and amounts theoretically to 0.34, while it is negligible in the perpendicular direction (along the $c$ axis).

A series of $dV/dI$ measured in magnetic field is shown in Fig. 1 (inset) with clearly seen two sets of the gap minima (double-gap features). The main panel in Fig. 1 displays the magnetic field dependence of the large and small gaps obtained by the routine BTK fitting of the curves from the inset. In spite of the rapid decrease in the intensity of the small gap minima with the field (a factor of two at 1 T, see the inset in Fig. 1), the small gap is not suppressed by low fields ($\lesssim 1$ T), and the estimated critical field 6-7 T (see Fig. 1) is much higher than that stated in Refs. 6,16. Moreover this field corresponds to $B_{c2}$ determined from the onset temperature in the broadened resistive transition in single crystals. Similar behavior of the small gap persisting up to 5 T was found in Ref. 18, where visual disappearance of the $\pi$-gap features in the PC characteristics was attributed to broadening of the spectra in the magnetic field.

Experimental data for $\Delta$ in Fig. 1 are in good agreement with the magnetic field dependence of the maximal pair potential $\Delta$ and averaged electron DOS $N(0, H)$ at zero energy for two ratios of the diffusion constants $D_1 = 2\pi T_c \xi_1^2$ for the $\sigma$ (1) and $\pi$ (2) bands. By courtesy of Koshelev and Golubov,

\begin{equation}
I_{exc} \approx \Delta/eR_N
\end{equation}

with $\Delta$ being the superconducting energy gap and $R_N$ being the PC resistance in the normal state.

We determined the reduced $I_{exc}(B)/I_{exc}(B = 0)$ either from the raw $I(V)$ or mostly by integrating the reduced $R^{-1}dV/dI(V)$ or $RdI/dV$ after subtracting the normal-state background. The use of the $I(V)$ curves provides less accurate results because of the resistance instability for some contacts during the field sweep.

For all investigated contacts the excess current depends on the magnetic field with the overall positive curvature (Fig. 2). At first, $I_{exc}(B)$ decreases abruptly and then more slowly above 1 T. This corresponds to the aforementioned drastic suppression of the $dV/dI(V)$ small-gap minima intensity by a magnetic field about 1 T and to the persistence of the residual superconducting minima on a further increase in the magnetic field. This is quite different from what is expected for $I_{exc}$ according to (1), taking into account that $\Delta(B)$ has, as a rule, a negative curvature (see Fig. 2).

Generally, the excess current, just like the net current through the contact, is proportional to the contact area $A$ (see, e.g., Eqs. (18), (19) in Ref. 14), i.e. $I_{exc} \sim A \Delta$. 

![Fig. 1: Magnetic field dependence of large and small superconducting energy gaps at 4.2 K (solid squares and triangles, left y-axis) obtained by a BTK fitting of the curves shown in the inset. Solid curves show magnetic field dependence of the maximal pair potential (right y-axis) for MgB$_2$ for $D_1 = D_2$ (see Fig. 2). Inset: symmetrized experimental $dV/dI$ curves in magnetic field (solid lines) for the single crystal MgB$_2$–Cu 2.2 $\Omega$ junction along the $ab$ plane with BTK fit (thin lines) from Ref. 14. Two separate sets of the gap minima around ±2.5 and ±7 mV are clearly seen in the low fields.](image1)

![Fig. 2: Magnetic field dependences of the maximal pair potential $\Delta$ and averaged electron DOS $N(0, H)$ at zero energy for two ratios of the diffusion constants $D_1 = 2\pi T_c \xi_1^2$ for the $\sigma$ (1) and $\pi$ (2) bands. By courtesy of Koshelev and Golubov.](image2)
Assuming that $I_{\text{exc}}$ is caused by the superconducting component of the current, which in the mixed state is determined by the superconducting volume (part) in the PC area, the coefficient $A$ in the above-mentioned formula should be effectively reduced by the contribution of the nonsuperconducting volume. Koshelev and Golubov calculated the magnetic field dependence of the electron density of states (DOS) $N(E)$ at $E=0$ averaged over the vortex unit cell. We assume that in the first approximation the averaged $N(0, B)$ can be regarded as a measure of the nonsuperconducting region in the mixed state, and, vice versa, $(1 - N(0, B))$ characterizes the superconducting phase portion. Thus, according to above reasoning, we suppose that

$$I_{\text{exc}} \propto w_L(1 - N_L(0, B))\Delta_L + w_S(1 - N_S(0, B))\Delta_S \quad (2)$$

with the weight factors $w_L$ and $w_S$ for large and small gaps, respectively ($w_L + w_S = 1$), $N_L,S(0, B)$ and $\Delta(B)_{L,S}$ are taken from Fig. 2 where $L \equiv 1$, $S \equiv 2$. Here, $I_{\text{exc}}$ is presented by (2) as a sum of two contributions from the $\sigma$ and $\pi$ bands weighted by $w_{L,S}$ factors, which along with $\Delta$ were derived from the fitting of the Andreev-reflection features in $dV/dI$ at zero field.

Figure 3 shows the magnetic field dependence of $I_{\text{exc}}$ for three different types of $dV/dI$ with visually distinct small, large and double gap structures. Here, we also plotted $I_{\text{exc}}$ calculated by (2). The most unexpected result is the observation of $dV/dI$ with large-gap minima only, which is discussed in Ref. 18. The large-gap minima are only slightly affected by magnetic fields of a few tesla. This is in contrast to the small-gap minima, which according to Refs. 14 should vanish above 1 T. The curve in the bottom panel was calculated taking $w_L$ from the fitting of the double-gap structure (see Fig. 1), while in panel (a) and (b), where only the small- or large-gap structures are seen, $w_L$ can vary from zero to its highest value 0.34. The latter $w_L$ value was used for the spectra in the middle panel in which only large-gap minima are seen. Evaluation of $w_L$ for the spectrum in panel (a) inset is not straightforward because the spikes present at higher energies mask the large gap features. However, selected $w_L = 0.15$ and $w_L = 0.34$ fit reasonably both zero-field $dV/dI$ and $I_{\text{exc}}(B)$ curves in panels (a) and (b), respectively.

In general, the experimental and calculated curves agree well in spite of the simple empiric model adopted for $I_{\text{exc}}$. The calculated curves describe qualitatively the experimental data, especially the abrupt initial decrease in $I_{\text{exc}}$, pronounced in the curves with the dominant small-gap features (Fig. 3a). In Fig. 3c), showing two curves with different $D_1/D_2$ ratios, it is seen that better correspondence can be reached with an intermediate ratio between $D_1$ values. The same occurs for the data in Fig. 3b) for the large-gap spectrum, though the experimental data for large-gap and small-gap spectra are closer to the cases with $D_1 = D_2$. This fact testifies that in this case the $\sigma$ band is closer to the clean limit, also mentioned in Ref. 18.

**IV. CONCLUSIONS**

We have investigated the excess current in PCs based on single crystals of MgB$_2$ in the magnetic field and proposed an empiric model for the excess current behavior in the mixed state. Using this model, a magnetic field dependence of the excess current was obtained, which is in qualitative agreement with experimental data. The anomalous magnetic field dependence of the excess current in PCs reflects the specific two-band structure of the superconducting order parameter and the spatial DOS.
behavior in MgB$_2$. Thus, $I_{exc}(B)$ can be used for evaluation of the diffusivity in both bands on the base of Koshelev and Golubov’s theory.

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