Evidence for two-dimensional nucleation of superconductivity in MgB$_2$

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Abstract

According to the crystal structure of MgB$_2$ and band structure calculations quasi-two-dimensional (2D) boron planes are responsible for the superconductivity. We report on critical fields and resistance measurements of 30 nm thick MgB$_2$ films grown on MgO single crystalline substrate. A linear temperature dependence of the parallel and perpendicular upper critical fields indicate a 3D-like penetration of magnetic field into the sample. Resistivity measurements, in contrast, yield a temperature dependence of fluctuation conductivity above $T_c$ which agrees with the Aslamazov-Larkin theory of fluctuations in 2D superconductors. We consider this finding as an experimental evidence of two-dimensional nucleation of superconductivity in MgB$_2$.

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I. INTRODUCTION

Recent discovery [1] of a medium-temperature superconductivity in magnesium diboride (MgB$_2$) raised questions about the origin and properties of superconductivity in this compound. MgB$_2$ has a hexagonal crystal structure with boron layers interleaved by magnesium layers. Due to this layered structure, normal state electric transport, as well as superconducting properties should be highly anisotropic. Band structure calculations [2,3] indicate that electrons at the Fermi level are predominantly derived from boron atoms. MgB$_2$ may be regarded as sheets of metallic boron with strong covalent intralayer bonding, separated by Mg layers with ionic interlayer B-Mg bonding. The strong B-B bonding induces enhanced electron-phonon interaction, so that the superconductivity in MgB$_2$ is mainly due to the charge carriers in the boron planes.

Experimental investigations on single crystals and c-oriented epitaxial and textured films (see, e.g., the review [4] and references therein) give evidence for a highly anisotropic superconducting gap. Measured critical magnetic fields usually show a pronounced anisotropy for c-oriented films and single crystals [4]. Applying the anisotropic Ginzburg-Landau model to these measurements, authors derive an effective mass anisotropy for the charge carriers of \(\gamma = m_{ab}/m_c \approx 0.15 - 0.3\). Thus, band structure calculations and experimental measurements strongly suggest that superconductivity nucleates at the quasi-two-dimensional (quasi-2D) boron planes, and then extends through the magnesium layers by a nanoscale proximity effect forming an anisotropic 3D superconducting state in the material.

In this Letter we present experimental evidence for 2D nucleation of superconductivity in a 3D magnesium diboride film. To demonstrate this, we measured the temperature dependence of excess conductivity caused by fluctuations above \(T_c\). If quasi-2D boron planes are responsible for the superconductivity, then the excess conductivity should exhibit 2D behavior although measured in a 3D sample. We found that the temperature dependence of the excess conductivity agrees well with the Aslamazov-Larkin [5] theory of superconducting fluctuations in 2D superconductors.

II. RESULTS AND DISCUSSION

The MgB$_2$ films were prepared by DC magnetron sputtering on single crystalline MgO (101) substrate according the procedure described in [6]. To compensate losses of magnesium due to its oxidation in plasma, a composite target was used which contained MgB$_2$ and metallic magnesium in approximately equal amounts. The Mg-MgB$_2$ pellet was sputtered in a 99.999% purity argon atmosphere at a pressure of 3 Pa. The substrate temperature during sputtering was held at 200 °C and then raised to 600 °C for several seconds at the final stage. At this final in situ annealing the plasma discharge was not switched off. X-ray studies revealed a strongly textured (101)-oriented structure of our films. Films of 30 nm thickness have been used for resistance and critical field measurements.

The superconducting transition temperature, \(T_c\), obtained by a conventional four-terminal resistive method at zero field, was about 19.5K. The upper critical fields parallel (\(B_{c2||}\)) and perpendicular (\(B_{c2\perp}\)) to the film plane have been measured using the 7T superconducting magnet of a ”MPMS XL Quantum Design” SQUID magnetometer.
The resistive transitions, \( R(T) \), at constant perpendicular magnetic field for one of the investigated samples are plotted in Fig.1. The transition width at zero field, according to a (10-90)\% \( R_n \) criterion, is about 0.3K and slightly increases in stronger magnetic field to about 1K at 6T. The temperature dependence of the critical fields is displayed in Fig.2. It shows a pronounced anisotropy, \( B_{c2\parallel}/B_{c2\perp} \approx 1.5 \), in accordance with previous studies, reporting values of 1.2 – 2 for \( c \)-oriented films and 2.4-2.7 for single crystals [4]. The temperature dependence of \( B_{c2\parallel}(T) \) is linear except for temperatures very close to the critical temperature. The \( B_{c2\perp}(T) \) dependence starts nearly linear, and then increases more rapidly. We obtain the Ginzburg-Landau coherence length, \( \xi_{GL}(0) \), from the slopes of \( B_{c2\parallel}(T) \) and \( B_{c2\perp}(T) \) close to the critical temperature [7],

\[
\xi_{GL}(0) = [-(dB_{c2}(T)/dT) (2\pi T_c/\phi_0)]^{-1/2},
\]

where \( \phi_0 \) is the magnetic flux quantum. Calculations according to (1) give \( \xi_{GL}(0) = 4.4 \) nm, \( \xi_{GL\perp}(0) = 6.8 \) nm, much less than the film thickness \( d = 30 \) nm. The linear temperature dependence of \( B_{c2\parallel}(T) \) gives evidence that the film is three dimensional with respect to superconductivity. Especially, the absence of a square-root temperature dependence of \( B_{c2\parallel}(T) \) clearly demonstrates that the films show no indication for 2D superconductivity. For the deviation of \( B_{c2\perp}(T) \) from the linear behavior several reasons may be responsible, such as: anisotropy of the energy gap, proximity effect due to the weakly superconducting Mg interlayers in the MgB\(_2\) compound [8,9]. The nonlinear behavior of \( B_{c2\perp}(T) \) is commonly observed in MgB\(_2\) (see Ref. [4]).

Using our data on the temperature dependence of the resistance at zero DC magnetic field we calculate the fluctuation conductance by the relation [3]

\[
\sigma'(T) = \frac{1}{R(T)} - \frac{1}{R_n} \propto (T/T_{cAL} - 1)^{D/2-2},
\]

where \( R_n \) is the normal state resistance, \( D \) is the effective dimensionality of a superconductor (\( D = 1, 2, 3 \)), and \( T_{cAL} \) is the Aslamazov-Larkin critical temperature [3]. If the effective dimensionality of superconducting fluctuations is \( D = 2 \), then according to Eq. (2) we expect a linear dependence of the inverse excess conductance on temperature:

\[
[\sigma'(T)]^{-1} = \frac{R_n}{\tau_{AL}} \frac{(T - T_{cAL})}{T_{cAL}},
\]

with

\[
\tau_{AL} = C_0 R_n^\square,
\]

\[
C_0 = \frac{e^2}{16\hbar} = 1.52 \times 10^{-5} \text{ } \Omega^{-1},
\]

where \( R_n^\square \) is the normal state sheet resistance of the film.

Fig. 3 shows the temperature dependence of the inverse excess conductance normalized by the normal state conductance. The intersection of the linear approximation by Eq. (3) with the abscissa gives the critical temperature \( T_{cAL} \), while the slope of the line provides the
value of $(\tau_{AL})^{-1}$. In Fig. 3 we also show the fit according to Eq. (2) for the case $D = 3$. Obviously, the 2D-fit describes the experimental data much better than 3D-fit. Using the experimental values of the slope of the 2D-fit we calculate the effective normal state sheet resistance by Eqs. (4) and (5):

$$R_{n}^{\square} = \frac{\tau_{AL}}{C_{0}} = 71 \Omega/\square.$$  \hfill (6)

For a homogeneous 2D film this value should be identical to that one obtained from the measurement of the resistance in the normal state above the critical temperature, $R_{n}^{\square, \text{exp}}$. Since, however, $R_{n}^{\square, \text{exp}} = 1.105 \Omega/\square$ is about 60 times smaller than the effective sheet resistance (6) our sample must be a stack of a large number of parallel boron sheets. The number of the sheets, $N_{\text{eff}}$, which are involved in the sheet resistance of our MgB$_2$ film, may be estimated as

$$N_{\text{eff}} = \frac{R_{n}^{\square, \text{eff}}}{R_{n}^{\square, \text{exp}}} = \frac{71}{1.105} \approx 64.$$ \hfill (7)

In that case the effective interlayer spacing of the boron sheets can be obtained from the film thickness, $d$, as follows

$$d_{eff}^{BB} = \frac{d}{N_{\text{eff}}} \approx 0.46 \text{ nm},$$ \hfill (8)

which is not far from the $c$-axis spacing $c = 0.3524$ nm [1]. Thus, we may conclude that the description of superconducting fluctuations above $T_c$ in the framework of a two-dimensional model is consistent with our experiment.

In summary, we have measured the resistance and critical fields of MgB$_2$ films prepared on MgO substrate. From the linear temperature dependence of the critical fields we established anisotropic three-dimensional superconductivity of our films. From the resistivity measurements we showed that the temperature dependence of fluctuation conductivity above $T_c$ agrees with the Aslamazov-Larkin theory for 2D superconductor. We consider this finding as an experimental evidence for two-dimensional nucleation of superconductivity in MgB$_2$.

III. ACKNOWLEDGMENTS

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Figure captions

Fig. 1. Resistive transitions, $R(T)$, for a 30 nm thick MgB$_2$ film at different values of the DC magnetic field $B_{\perp}$: 0 - 0T, 1 - 0.3T, 2 - 0.6T, 3 - 0.9T, 4 - 1.8T, 5 - 2.7T, 6 - 3.6T, 7 - 4.5T, 8 - 5.4T, 9 - 6.9T.

Fig. 2. The temperature dependences of the parallel critical magnetic field $B_{c2\parallel}(T)$ (solid circles) and perpendicular critical magnetic field $B_{c2\perp}(T)$ (solid squares) obtained from the midpoints of $R(T)$ data of Fig. 1.

Fig. 3. The temperature dependence of the inverse fluctuation conductivity, $[\sigma'(T)]^{-1}$, normalized by the normal state value, $\sigma_n$, for the resistive transition in zero field (data of curve ”0” from Fig. 1). The straight line is the fit of experimental data by Eq. (3) for 2D-fluctuations, and the curve is the fit for the 3D-case.
Fig. 1, A.S. Sidorenko et al.
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MgB$_2$ 17/10;

- $B_{c2\parallel}$
- $B_{c2\perp}$
Fig. 3, A.S. Sidorenko et al

\[ \frac{\sigma_n}{\sigma'} \]

MgB\(_2\) 17/10

\[ T_c^{\text{AL}} (2D) = 19.57 \text{ K} \]