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Superconducting anisotropy and evidence for intrinsic pinning in single crystalline MgB_2

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We examine the superconducting anisotropy $\gamma_c = (m_c/m_{ab})^{1/2}$ of a metallic high-T_c superconductor MgB_2 by measuring the magnetic torque of a single crystal. The anisotropy γ_c does not depend sensitively on the applied magnetic field at 10 K. We obtain the anisotropy parameter $\gamma_c = 4.31 \pm 0.14$. The torque curve shows the sharp hysteresis peak when the field is applied parallel to the boron layers. This comes from the intrinsic pinning and is experimental evidence for the occurrence of superconductivity in the boron layers.

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I. INTRODUCTION

Since the discovery of superconductivity in MgB_2 (Ref. 1) considerable progress has been made in determining the physical properties of this material. The new materials are metallic and hence promising when considering the applications in the various fields. The extremely high T_c (39 K) sheds doubt on whether or not the superconductivity can be explained within a conventional BCS framework. Tunneling studies show that the material is reasonably isotropic and has a well-developed *s*-wave energy gap.[2,3] The anisotropy parameter $\gamma_c = (m_c/m_{ab})^{1/2}$ of MgB_2 in the literature ranges from 1.2 to 9 in polycrystalline samples.[4] Therefore, it is highly desirable to investigate the fundamental properties of MgB_2 by using a single crystal. Recently, Xu *et al.*[5] succeeded in synthesizing the single crystals by the vapor transport method and reported the superconducting properties of MgB_2.

The first-principles calculation by Kortus *et al.*,[6] by Choi *et al.*,[7] and by Yildirim *et al.*[8] suggested that the boron layers govern the superconductivity. The boron isotope effect on T_c supports this idea.[9] However, the experimental confirmation of the superconductivity in the boron layers is not thoroughly convincing so far.

Torque is a sensitive tool for probing the various kinds of anisotropy, and has been successfully applied to investigate the highly anisotropic high-T_c cuprates. The electronic anisotropy of high-T_c cuprates was investigated by Farrell *et al.*[10] and Ishida *et al.*[11] The high-T_c cuprates are characterized by the extreme electronic anisotropy $\gamma_c = \sqrt{m_c/m_{ab}} = 7-200$ as well as the layered structure of superconductivity. The superconductivity is governed by the CuO_2 layers or by the CuO_2 bilayers. An alternative stacking of the CuO_2 layer and the blocking layer is a key concept both in crystal structure and in the occurrence of the superconductivity. This is also the origin of the intrinsic pinning for vortices in high-T_c superconductors. The MgB_2 structure consists of an alternative stacking of the boron layer and the magnesium layer, too. It is of special interest to investigate the similarity and dissimilarity between this material MgB_2 and the cuprate superconductors.

It is crucial to discriminate the intrinsic pinning from various other pinning sources. The magnetic torque has an advantage to see the vortex pinning as a function of angle with respect to a crystalline axis. Since the intrinsic pinning works effectively when the field is almost in parallel to the CuO_2 planes, it manifests as a hysteresis peak in torque.[12,13] Therefore, a torque is a sensitive probe for sensing an intrinsic (directional) pinning.

In this paper, we report the electronic anisotropy of MgB_2 by means of the magnetic torque. We also describe evidence for the intrinsic pinning in MgB_2 when the field is applied parallel to the boron layers. This ensures that the superconductivity occurs in the boron layers.

II. EXPERIMENT

A. Sample

The details of the single-crystal preparation of MgB_2 are reported by Xu *et al.*[5] They reported that the onset temperature of superconductivity is 38.6 K. Because of the severe volatility of Mg and the high melting point of B, MgB_2 single crystals were grown in a closed system. The starting material of Mg was 99.99% pure and B was 99.9% pure. The starting materials, with a molar ratio of 1:1.9 were sealed inside a molybdenum crucible of internal diameter 10 mm, and length 60 mm by the electron-beam welding. The molybdenum crucible was used in a high-frequency induction furnace. The crucible was first heated to 1400 °C at a rate of 200 °C/h and kept for 2 h, then slowly cooled to 1000 °C at a rate of 5 °C/h, and finally cooled to room temperature by switching off the power. A platelike single crystal of MgB_2 ($\sim 0.11\ \mathrm{mm}^2 \times 14\ \mu\mathrm{m}$) was used for the torque measurements. The *c* axis was perpendicular to the plate. The sample weight was too tiny to measure by our electronic balance of resolution 0.01 mg.

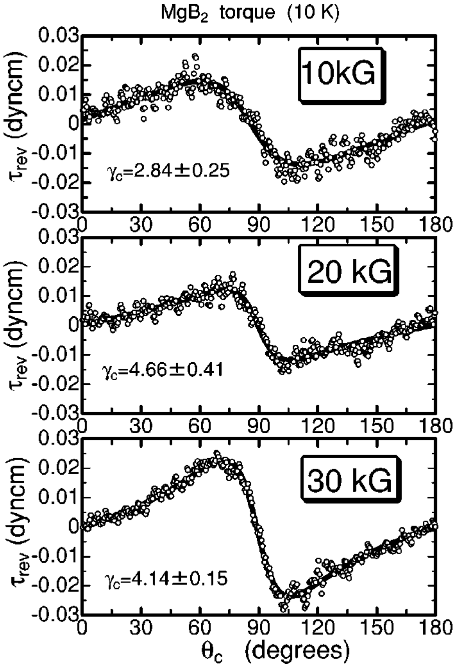

FIG. 1. The reversible torque τ_{rev} of MgB_2 as a function of angle θ_c at 10 K (10 kG, 20 kG, 30 kG). The reversible torque is determined as $\tau_{rev}(\theta)=[\tau_{inc}(\theta)+\tau_{dec}(\theta)]/2$ where $\tau_{inc}(\theta)$ and $\tau_{dec}(\theta)$ are the torques as a function of increasing and decreasing angle. The torque curves are analyzed the Kogan model by fixing $\eta H_{c2}=60$ kG (see γ_c of the figures).

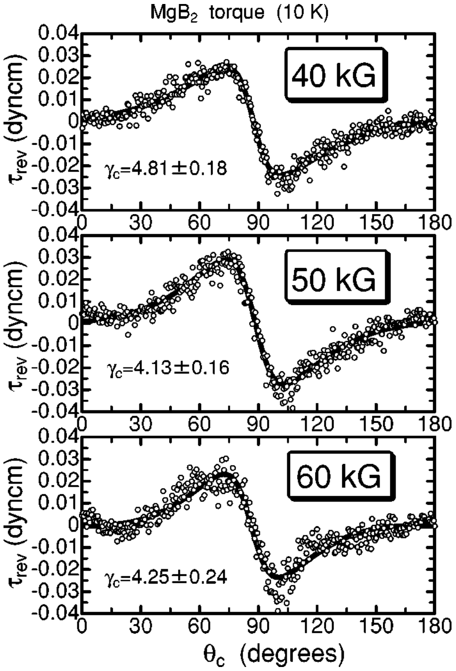

FIG. 2. The reversible torque τ_{rev} of MgB_2 as a function of angle θ_c at 10 K (40 kG, 50 kG, 60 kG). The reversible torque is determined as $\tau_{rev}(\theta)=[\tau_{inc}(\theta)+\tau_{dec}(\theta)]/2$ where $\tau_{inc}(\theta)$ and $\tau_{dec}(\theta)$ are the torques as a function of increasing and decreasing angle. The torque curves are analyzed the Kogan model by fixing $\eta H_{c2}=60$ kG (see γ_c of the figures).

B. Torque

A split-type superconducting magnet changed a magnetic field continuously from -60 kG to $+60$ kG, and had a variable temperature insert from 4 K to 300 K. A torque detection system was attached on the top of the insert. A phosphor bronze string hung a balance arm, a feedback coil, and a quartz sample rod in a helium-gas atmosphere from the main flange. The feedback coil (300 turns of a 0.075-mm Cu wire) was located in a special hollow cylindrical NdFeB permanent magnet (Magnetic Solutions) of a transverse field of 5000 G to 8000 G. A sample torque could be canceled by a controlled torque given by a torque detection mechanism at the top of the insert. We used an optical position sensor to maintain the sample direction. The sample could be rotated by a stepper motor (a resolution of 0.0036°). The torque dynamic range was from -10^3 dyn cm to $+10^3$ dy ncm with a sensitivity of 10^{-3} dyn cm.

III. RESULTS AND DISCUSSIONS

We measured the torque of single crystalline MgB_2 as a function of θ_c. The angular step was chosen as 0.5°. The irreversible torque was extracted by $\tau_{irr}(\theta)=[\tau_{dec}(\theta)-\tau_{inc}(\theta)]/2$ and the reversible torque was obtained as $\tau_{rev}(\theta)=[\tau_{inc}(\theta)+\tau_{dec}(\theta)]/2$ where $\tau_{inc}(\theta)$ and $\tau_{dec}(\theta)$ are the torques as a function of increasing and decreasing angle, respectively.

In Figs. 1 and 2, we show the reversible torque τ_{rev} of MgB_2 at 10 K (10 kG, 20 kG, 30 kG) and the reversible torque τ_{rev} of MgB_2 at 10 K (40 kG, 50 kG, 60 kG), respectively. The shape of the torque curves in Figs. 1 and 2 is similar to the torque curve of $YBa_2Cu_3O_{7-\delta}$.[11] This indicates that the MgB_2 superconductor is anisotropic with respect to the *c* axis. In the three-dimensional anisotropic London model in the mixed state, the angular dependence of the torque is given by Kogan[14] as

$$\tau_{rev}(\theta_c)=\frac{\phi_0 HV}{16\pi\lambda^2}\,\frac{\gamma_c^2-1}{\gamma_c^{1/3}}\,\frac{\sin 2\theta_c}{\epsilon(\theta_c)}\ln\left\{\frac{\gamma_c\,\eta H_{c2}^{\perp}}{H\epsilon(\theta_c)}\right\}, \qquad (1)$$

where $\epsilon(\theta_c)=(\sin^2\theta_c+\gamma_c^2\cos^2\theta_c)^{1/2}$, θ_c is the angle between the applied field and the *c* axis, $\gamma_c=\sqrt{m_c/m_{ab}}$, $H_{c2}^{\perp}$ is the upper critical field perpendicular to the ab plane ($\eta\sim 1$), and V is the sample volume. This equation is relatively simple, and has frequently been employed in the literature to analyze the electronic anisotropy of various high-T_c cuprates.[10,11,15] The computer fitting of τ_{rev} to the Kogan model gives the anisotropy parameter $\gamma_c=2.8-4.8$ where ηH_{c2} is fixed to 60 kG.[5]

As shown in Fig. 3, the torque curve measured in 10 kG at 10 K has a hysteresis against the angle scans. The torque as a function of increasing as well as decreasing angle has a sharp peak at $\theta_c\simeq 90°$. This is well known as an intrinsic pinning peak for the high-T_c cuprates.[12,11] The dashed line is the reversible component (see the fitted line in the top figure of Fig. 1). The peak appearing near 90° represents the manifestation of intrinsic pinning in this superconductor. This is experimental confirmation of the superconductivity in the

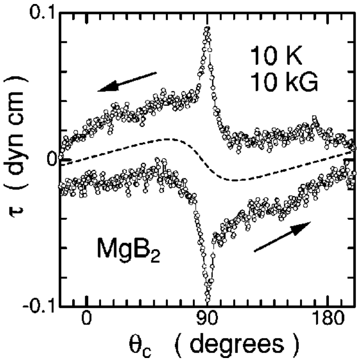

FIG. 3. The torques as a function of increasing as well as decreasing angle are presented in 10 kG at 10 K. The dashed line is the reversible component (see top figure of Fig. 1). The peak appearing near 90° represents the manifestation of intrinsic pinning in this superconductor. This is clear evidence for layered superconductivity in the boron layers.

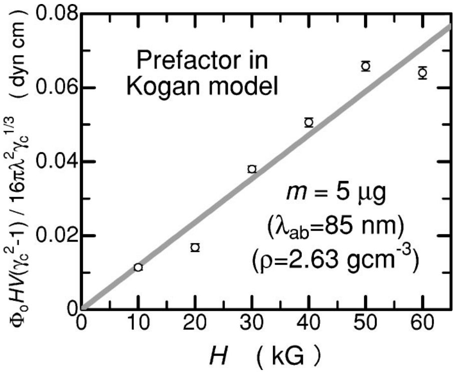

FIG. 4. A prefactor $\phi_0 HV(\gamma_c^2-1)/16\pi\lambda^2\gamma_c^{1/3}$ of the Kogan formula as a function of H. From the slope, the sample mass is estimated to be approximately 5 μg.

boron layers.[6–8] The remarkable hysteresis of the torque curve give rise to the uncertainty in the reversible torque obtained by $\tau_{rev}(\theta)=[\tau_{inc}(\theta)+\tau_{dec}(\theta)]/2$. Actually, γ_c in 10 kG is appreciably less than those in other fields at 10 K. A tiny intrinsic pinning peak can be seen in the torque curve at 20 kG. Note that the torque curves are almost reversible for 30 kG, 40 kG, 50 kG, and 60 kG.

The γ_c is almost independent of field between 20 kG and 60 kG at 10 K. We omitted γ_c in 10 kG to obtain the averaged $\langle\gamma_c\rangle=4.31\pm0.14$. This is somewhat larger than those reported in the literature.[4]

Angst *et al.*[16] also reported the torque measurement of MgB_2. Their measurement regime is complimentary to ours. They mainly use the torque as a sensitive means of determining H_{c2} as a function of angle θ_c. However, the determination of H_{c2} is dependent on the criterion of the torque onset, and their criterion contains a target parameter γ_c. The upper critical field $H_{c2}(\theta_c)$ thus obtained is analyzed by the effective-mass model. They obtained $\gamma=6$ at 15 K and $\gamma=2.8$ at 35 K. They also used the Kogan model to analyze the torque data and found the field dependence of γ_c. They interpreted it in terms of the double gap structure of MgB_2. We note that this is not the case in our torque measurements because γ_c is almost independent of field at 10 K.

We attempted to measure the temperature dependence of the torque curve in 60 kG, but the signal-to-noise ratio was not satisfactory enough to analyze the torque data. This is due to the small size of the MgB_2 crystal. Our results were inconclusive regarding the temperature dependence of γ_c. Measurements using a larger crystal are desirable for the detailed studies of the MgB_2 system.

Finally, we estimate a weight of our MgB_2 sample from the torque amplitude. In the Kogan model, we obtain a prefactor of $\phi_0 HV/16\pi\lambda^2$ by the least-squares fitting where the penetration depth should read as $\lambda=(\lambda_c\lambda_{ab}^2)^{1/3}$. In Fig. 4, we plot $\phi_0 HV/16\pi\lambda^2$ as a function of H. The data points are approximately fitted by a straight line. From the slope, one can determine the sample volume V. By assuming $\lambda_{ab}=85$ nm,[4] the density $\rho=2.63$ g/cm^3, and $\gamma_c=4.31$ we estimate the mass m of our sample as ~5 μg. We note that the mass calculated from the measured size of the crystal and the density of MgB_2 is approximately 3.3 μg.

IV. CONCLUSIONS

The torque curves at 10 K are almost reversible in fields larger than 20 kG. The electronic anisotropy of MgB_2 is determined by the torque as $\gamma_c=4.31\pm0.14$. The new superconductor exhibits an intrinsic pinning at 10 K in 10 kG when the field is applied parallel to the boron layers. There is a modulation of the order parameter in MgB_2 along the c axis. This indicates that the boron layers, as suggested from the first-principles calculations,[7] govern the superconductivity. The MgB_2 superconductor is rather similar to the high-T_c cuprates while the anisotropy of MgB_2 is moderate compared to the cuprates.

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