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Anomalous field dependence of anisotropy observed in MgB_2 single crystals with a torque method

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Abstract

The field dependence of anisotropy in the mixed state of MgB_2 single crystals is studied using torque magnetometry. At all temperatures measured, the anisotropy parameter γ, derived from the angular dependence of magnetic torque τ, increases with increasing field H and shows a plateau with a almost constant value of ~4.5, indicating that the isotropic π band contribution to the superconductivity weakens with H and only the anisotropic σ band contribution remains in the plateau region. In the low field region below the plateau, we found a change in the functional form of $\gamma(H)$ at $H = H^*$. In addition, the step-like decrease in the H dependence of $d(\tau/H)/dH$ is observed at H^*. These anomalies can be related to the change in the vortex lattice structure accompanied by the decrease of the π band contribution.

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1. Introduction

In addition to the high critical temperature of 39 K, one of the most peculiar and important features of MgB_2 [1], is the fact that this material has two superconducting gaps [2–8], associated with different kinds of bands forming the Fermi surfaces. One is the large gap Δ_σ (~7 meV) which originates from the σ bands formed by p_{xy} orbitals parallel to the boron network plane. The other is the small gap Δ_π (~2–3 meV) which originates from the π band formed by p_z orbitals perpendicular to the boron plane. From the band structure calculation [2,3,9] it is well established that the σ bands have hole-type and quasi-two dimensional character, while the π bands have electron-type and isotropic three dimensional one. Due to the different parity and orbital directions, the mixing of the carriers between two kinds of bands is very small, meaning the negligible inter-band scattering of carriers [10]. This may lead to different field dependence between Δ_σ and Δ_π. Indeed, a number of experiments, such as specific heat [11], thermal conductivity [12] and flux flow resistivity [13], show the unusual field dependence as compared with that for the conventional s-wave superconductors. Most measurements appear to indicate that the contribution of the π band to the superconductivity is suppressed around $H = 1$ T or above it at low temperatures, and the anisotropic upper critical field at low temperature is determined by the anisotropic σ band superconductivity. The disappearance of Δ_π around $H = 1$ T has been also confirmed in the point contact measurements in magnetic fields [14].

In this situation, the questions, which remain unsettled, are how the π band contribution to the superconductivity suppressed, and whether any changes in the vortex structure

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occur due to the decrease of the π band contribution. For the former, it is not so clear whether the disappearance of Δ_π is a phase transition or a crossover phenomenon. For the latter, the reorientation of the flux line lattice has been observed in the measurements of small angle neutron scattering at 2 K recently [15]. It is necessary to check this phenomenon with different methods and in a wide temperature range in order to compare it with the theoretical explanation to this phenomenon [16]. In this work, we address the above questions with the torque magnetometry. The torque, $\tau = |\boldsymbol{M} \times \boldsymbol{H}|$ with M the magnetization and H the applied magnetic field, is the quantity, which contains the information of anisotropy parameter $\gamma = (m_c/m_{ab})^{1/2}$, as well as the magnitude of M [17]. Here, m_c and m_{ab} are electron effective mass parallel to the c axis and the ab plane, respectively. If a change in the relation between the two band contributions with different dimensionalities or a change in the structure of vortex lattice occurs, that may be detected in the measurements of τ. Thus, we have performed the torque measurements as a function of H and the angle θ between the c axis and H at various temperatures T, and then examined the field dependence of γ and M.

2. Experimental

Single crystals of MgB_2 were grown by the high pressure method [18] and the encapsulation method [19]. In this paper, we present the results for the crystal by high pressure method with a size of $\sim 0.1 \times 0.1 \times 0.05\ \mathrm{mm}^3$, since the samples from both techniques reveal similar results. The superconducting transition temperature T_c at 10 mT and upper critical field $H_{c2}(\theta = 10°)$ at 4.2 K of the sample are 37.0 K and 3.0 T, which are estimated from T and H dependence of τ using the method as described below. The small value of H_{c2} indicates that the sample is very clean.

The magnetic torque τ was measured utilizing a piezoresistive cantilever unit developed commercially for the AFM [20], which contains two piezo resistances, one for the cantilever with sample and the other for the compensation of the background resistance. Making a bridge circuit using these resistances, we detected the unbalance voltage between the compensation resistance and that for the cantilever, which is proportional to the torque value.

3. Results and discussion

The anisotropy parameters γ are derived by fitting $\tau(H)$ data using Kogan formula [17], described as,

$$\tau_{eq}(\theta) = A \frac{\sin 2\theta}{\varepsilon_\theta} \ln\left(\frac{\gamma \eta H_{c2}^{\parallel c}}{H \varepsilon_\theta}\right) \tag{1}$$

where $\varepsilon_\theta = (\sin^2\theta + \gamma^2\cos^2\theta)^{1/2}$, A is a parameter independent of θ, and η is a constant of order unity. Although Kogan has also proposed another formula of $\tau(\theta)$ in case that the anisotropy of the upper critical field γ_H is different from the anisotropy of the penetration depth γ_λ as observed in MgB_2 [21], we assume that $\tau(\theta)$ is described by Eq. (1) with a single H dependent anisotropy parameter $\gamma(H) = \gamma_H(H) = \gamma_\lambda(H)$ as suggested by Lyard et al. [22]. In this idea, the observed difference between γ_H and γ_λ comes from the difference of the fields at which they are measured. We also assume that γ is almost independent of θ (field direction), since the H dependence of γ is considered to originate from the decrease of the almost isotropic π band contribution with H. This assumption is consistent with the results of the point contact measurements [14], where the feature of Δ_π in the tunnel conductance vanishes at the same field for $H \parallel c$ and $H \parallel ab$.

Fig. 1 shows the typical results of the fitting at 15 K with γ as a fitting parameter. In this fitting we determine $\tau_{eq}(\theta)$ as $(\tau_{down}(\theta) + \tau_{up}(\theta))/2$, where $\tau_{down}(\theta)$ and $\tau_{up}(\theta)$ mean $\tau(\theta)$ with decreasing and increasing angle. Since the hysteresis between the two processes is very small due to the weak pinning in our sample, this average becomes a good approximation to the thermal equilibrium torque τ_{eq}. The agreement between the data and the fitting looks good. However, small deviation between the data and the fitting curve appears. This may come from the two band effect, or come from small deviation from the complete isotropic contribution of the π band to the superconductivity. In this work, we fit the data as the maximum position of the data coincides with the curve.

In Fig. 2, the γ values derived from the method described above are plotted as a function of H for several temperatures. As a common tendency, γ increases with H from ~ 2 at 0.1 T and shows a plateau with a constant value ~ 4.5 around 1.5 T. This indicates that the isotropic π band contribution to the superconductivity weakens with H, and only the anisotropic σ band contribution remains in this plateau region. It is noted that at a low field below the plateau, a change in the functional form occurs in $\gamma(H)$ at a characteristic field H^*. The same type of anomaly is also observed in the sample grown by the encapsulation method, indicating that the phenomenon is independent

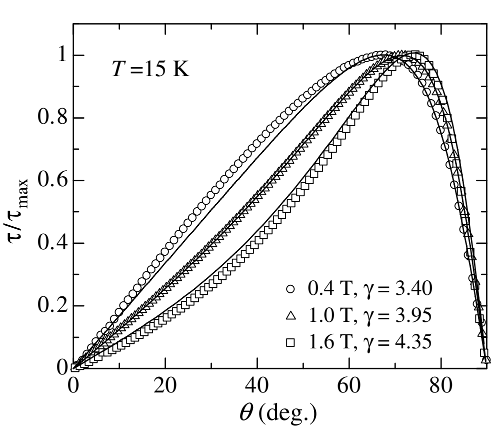

Fig. 1. Typical torque vs. angle curves fitted using Kogan formula (Eq. (1)). Symbols and lines denote the data and the fitting lines, respectively.