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Observation of vortex phase transition in MgB_2 single crystals by a magnetic torque method

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Abstract

The magnetic torque measurements were performed on two MgB_2 single crystals with the different values of upper critical fields H_{c2} (3.7 T and 3.1 T at 4.2 K). At low temperatures, the irreversible torque-vs-field curves $\tau(H)$ in the both samples show the peak effect, accompanied by the field-history dependence, close to H_{c2} for all the field directions measured. With increasing temperature, the peak in $\tau(H)$ becomes less pronounced, and disappears around $T = 27$ K. In the sample with smaller H_{c2}, $\tau(H)$ curves display diamagnetic steps at the higher temperatures. On the other hand, in the sample with larger H_{c2}, such a step is not observed. Our results suggest that the order–disorder transition around the peak transforms to the first-order melting transition, which is very sensitive to the degree of disorder.

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1. Introduction

Since the recent discovery of the superconductivity in MgB_2 around 39 K [1], a lot of studies have been performed to understand its properties from the viewpoint of both fundamental physics and practical application [2]. It is now well established that this compound is a phonon-mediated s-wave superconductor [3,4] with two superconducting gaps [5,6], which are weakly coupled and originate from two kinds of boron bands, two dimensional σ bands and three dimensional π bands, respectively. One of the peculiar feature of MgB_2 is the unusual temperature dependence of upper critical field H_{c2} or anisotropy parameter $\gamma = H_{c2}^{\perp c}/H_{c2}^{\parallel c}$ [7–9], where $\perp c$ and $\parallel c$ denote the

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filed direction is perpendicular and parallel to the c-axis, respectively. The relation between the origin of its dependence and the existence of two gaps may be unsettled problem.

Turning our attention to the mixed state, not so many things about the vortex matter phase diagram have been clarified as compared with that of high-T_c cuprate superconductors. MgB_2 is a type-II superconductor with the GL parameter $\kappa = 5 \sim 8$ [8] and $\gamma = 2 \sim 6$ [7–9], which are intermediate between high-T_c and low-T_c conventional superconductors, as well as relatively high critical temperature T_c. Since these parameters strongly affect the superconducting fluctuation and so the condition of vortex-phase transitions, MgB_2 can be a good model system in understanding the universal properties of the vortex matter phase diagram with approaching both from high-T_c and low-T_c side. Recently, there are a few reports for the possible existence of the first-order melting transition of the ordered Bragg glass (or vortex lattice) phase in the measurements of local moments [10] and transport properties [11], and the order–disorder transition from the Bragg glass phase to the amorphous vortex glass in the measurements of magnetic torque and magnetization curves [12,13], in addition to H_{c2} and lower critical field H_{c1}. It is still important to check these phenomena with the various samples with different degree of disorder using the various methods.

In this work, we have performed the detailed measurements of magnetic torque τ as a function of magnetic field H, temperature T on two MgB_2 single crystals with different degrees of disorder. In addition to confirming the peak effect in torque-vs-field curve $\tau(H)$ close to $H_{c2}(T)$ line at low temperatures, which is caused by the order–disorder phase transition, the step-like behavior, corresponding to the first-order melting transition, is examined at high temperatures. We discuss the vortex matter phase diagram for MgB_2 and the sample dependence of it.

2. Experimental

Single crystals of MgB_2 were grown by the encapsulation technique using a vacuum sealed Mo crucible which contains a C crucible inside. After the heat treatment of Mg and B chunks in the crucible at 1350–1400 °C for 200 h, we obtained the shiny single crystals with smooth surfaces and a typical size of $0.15 \times 0.15 \times 0.05\ mm^3$. The details of sample preparation are described in Ref. [14]. Two crystals #1 and #2 were chosen for the measurements from different batches. From the measurement of T dependence of magnetization at 10 mT with a SQUID magnetometer and H dependence of torque as described below, T_c (10 mT) and $H_{c2}^{\|c}(4.2\ K)$ are estimated to be 37.0 K and 3.7 T for crystal #1, and 37.5 K and 3.1 T for crystal #2, respectively. Although the dHvA oscillations are observed in both crystals around 180 mK [14], indicating that both crystals are clean, the lower H_{c2} and higher T_c in #2 may imply that it contains smaller amount of disorder than #1. Especially, the Dingle temperature of crystal #2, obtained from the slope in the Dingle plot of dHvA oscillations, is 15 K [14]. This is nearly the same as the values for the samples prepared by the high pressure synthesis [15,16].

The magnetic torque was measured utilizing a piezo-resistive cantilever developed commercially for the AFM [17]. We detected the unbalance voltage between the compensation resistance and that for the cantilever in a bridge circuit. In this paper, we mainly report for the field dependence of torque $\tau(H)$ at fixed temperature T and angle θ between directions of H and the c-axis. Before each measurement of $\tau(H)$ curve, the sample was warmed up to 45 K, and cooled down to the desired temperature in zero field. Then we started to sweep the magnetic field with a rate of 0.1 T/min.

3. Results and discussion

Typical $\tau(H)$ curves for crystal #1 at $\theta = 10°$ are shown in Fig. 1. At low temperatures, the data reveal peak effect just below H_{c2} (denoted by solid triangles) with a maximum in the torque hysteresis $\Delta\tau(H) = \tau_{down}(H) - \tau_{up}(H)$. Here, $\tau_{down}(H)$ and $\tau_{up}(H)$ mean $\tau(H)$ with decreasing and increasing field, respectively, and H_{c2} is determined as the cross point of two extrapolated straight line for $M_{ave}(H) = (\tau_{down}(H) + \tau_{up}(H))/2H$ drawn from