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Anisotropy of the upper critical field in c-axis oriented MgB_2 thin films*

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C-axis oriented MgB_2 thin films were synthesized on single-crystal MgO (111) substrates using a chemical vapour deposition technique. The as-formed films revealed a sharp superconducting transition temperature of 38K with the transition width 0.2K. The temperature dependence of the upper critical magnetic field $H_{c2}(T)$ in the films was determined via resistivity for magnetic field H parallel and perpendicular to the c axis of the films. Using the Werthamer–Helfand–Hohenberg formula, we obtained the anisotropy ratio of the upper critical field γ=1.2.

Keywords: MgB_2 thin films, anisotropy, upper critical field, chemical vapour deposition
PACC: 7475, 7530G, 8115H

1. Introduction

Since the discovery of MgB_2 superconductors, extensive studies have been made on its superconducting properties.[1–3] One of the basic properties of MgB_2 is the anisotropy of the upper critical field H_{c2} derived from its layered crystal structure. Anisotropy is very important both for basic understanding of this material and practical applications, strongly affecting the pinning and critical current. The question related to the anisotropy degree of MgB_2 is still unresolved. Reported values of $\gamma = H_{c2}^{ab}(0)/H_{c2}^{c}(0)$ spread over a wide range depending on the measurement techniques and the sample forms. Values of γ determined from resistivity on textured crystallites, c-axis oriented films, single crystals and polycrystals have been reported to be 1.2, 1.2–1.8, 2.6–3 and 6, respectively.[4–9]

In order to clearly evaluate the anisotropy in MgB_2, measurements should be performed on single crystals or oriented thin films. In this paper, we report the anisotropy of H_{c2} by the measurement of resistive transition curves in magnetic fields on a high-quality c-axis oriented MgB_2 film. The sample was synthesized by chemical vapour deposition (CVD) technique. Compared with the physical vapour deposition, a most widely used method for growing MgB_2 thin films, CVD has the advantages of simple apparatus, high deposition rate, ability to coat complex shapes and capability for large area deposition.

2. Sample preparation and characterization

MgB_2 thin films were prepared by a combined approach of CVD and magnesium diffusion, as previously described.[10] The single-crystal MgO (111) was chosen as substrate due to the hexagonal surface symmetry with a lattice mismatch with MgB_2 less than 3%. The boron films were prepared on MgO (111) by CVD at a substrate temperature of 720°C. Then the insulating precursors were annealed at 890°C for about 40min in the presence of high purity magnesium (99.99%). The resulting superconducting MgB_2 films show a shiny gold-coloured appearance with the two-probe resistance of about 1Ω. X-ray diffraction (XRD) of the as-formed films revealed strong (00l) reflections, indicating a high degree of c-axis orientation (Fig.1(a)). The full width at half maximum of the

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rocking curve was only 1.3° for the (002) peak, further confirming an excellent c-axis orientation (Fig. 1b). From resistance measurement, we obtained the superconducting transition temperature T_c=38K, transition width ΔT=0.2K, and residual resistivity ratio RRR=2.8 (Fig.1(c)). Critical current densities are not reported in detail here, but a value of 10^7A/cm^2 has been achieved at 10K in zero field, revealing the high quality of the sample.

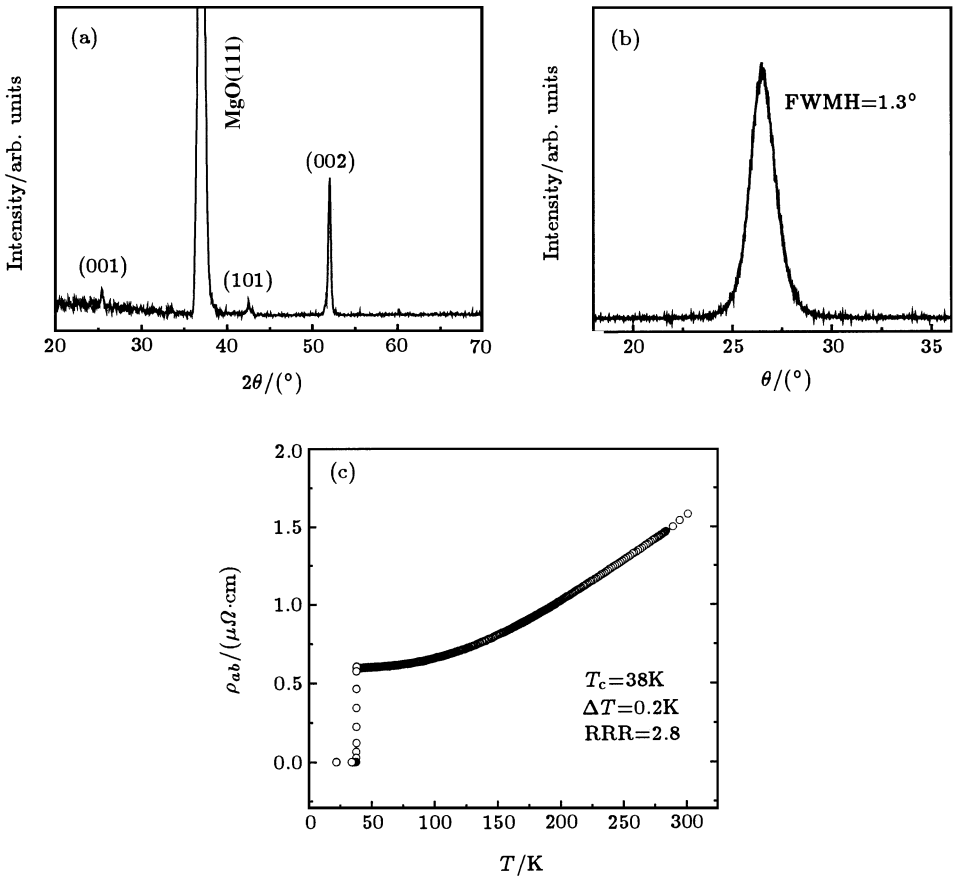


Fig.1. (a) θ–2θ scan and (b) θ-rocking curve of the (002) peak for the MgB_2 thin film on MgO (111) substrate, revealing high c-axis orientation of the sample. (c) The resistivity vs temperature for the same sample.

3. Measurement and results

The anisotropy of the upper critical field of the c-axis oriented MgB_2 thin films was determined by the measurement of resistive transition curves in magnetic field. Electrical resistance measurement as a function of temperature in applied magnetic field up to 5T were performed in a Quantum Design superconducting quantum interference device (SQUID, MPMS 5.5T) by using a four-probe dc resistance technique. The magnetic field was applied parallel and perpendicular to the film surface, with the current always in the plane of the film and perpendicular to the magnetic field. To make good electrical contact, four silver pads were evaporated on the surface of the sample and copper wires 0.1mm in diameter were then attached to the pads with silver epoxy.

Figure 2 shows the normalized resistivity as a function of temperature at various magnetic fields both parallel and perpendicular to the c-axis ($H//c$ and $H//ab$). As observed in the high-T_c cuprate superconductors, with the increase of the magnetic field, the T_c decreases and the transition width becomes broader. However, the behaviour of the resistive superconducting transition in applied magnetic field for MgB_2 differs somewhat from the high-T_c superconductors, in which a remarkable field-broadened transition is observed when the field is applied.[11–12]

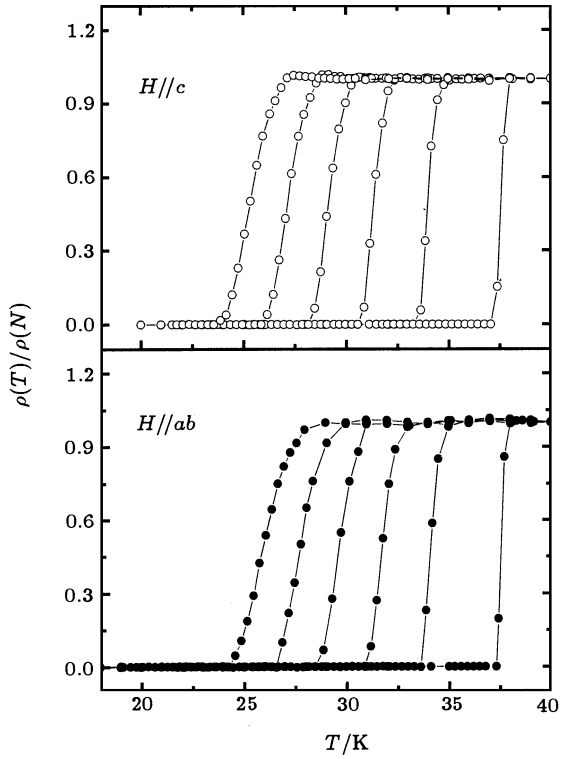


Fig.2. Normalized temperature dependence of resistivity (ρ–T) curves for the c-axis oriented MgB_2 film with the field parallel and perpendicular to the c-axis ($H//c$ and $H//ab$); from left to right the traces correspond to fields of 5, 4, 3, 2, 1 and 0T.

Figure 3 shows the curves of the temperature dependence of the upper critical field H_{c2} for the MgB_2 sample with $H//c$ and $H//ab$. The H_{c2} is derived from the data of Fig.2 by using the criterion of the resistive onset temperature. In Fig.3, there is a strong suppression of $T_c(H)$ at low field both for $H//c$ and $H//ab$, which shows an upward curvature near T_c, consistent with previous reported results for MgB_2.[13–15] A similar upward curvature near T_c in the H_c–T plot has been observed in intermetallic borocarbide compounds (Y–Ni–B–C, Lu–Ni–B–C single crystals),[16] high-T_c cuprate superconductors (Y–B–C–O, Ti–Ba–Ca–Cu–O, and Bi–Sr–Ca–Cu–O single crystals or thin films),[17–19] and A-15 superconducting compounds (Nb_3Sn and V_3Si).[20] Shulga *et al* ascribed the positive curvature of H_{c2} (T) near T_c in MgB_2 to the interband coupling by using a multi-band Eliashberg model for superconductors in the clean limit.[21] Further work is required to confirm this point. The upward curvature in H_{c2} (T) near T_c makes it difficult to apply the standard Werthamer–Helfand–Hohenberg (WHH) theory because the WHH theory predicts a linear temperature dependence of H_{c2} (T) near T_c. We note that the H_{c2} (T) curves in Fig.3 show a linear behaviour at high field, and we can therefore apply the WHH theory in this region:

$$H_{c2}(0) = 0.69\left(\frac{dH_{c2}}{dT}\right)T_c'. \quad (1)$$

Referring to Fig.3, the slope in Eq.(1) is taken as to be tangent to the $H_{c2}(T)$ curve at highest available field (5T) for our measurement and T_c' is the intersection of this tangent with the temperature axis.[22] Thus we obtain the values H_{c2}^c (0)=12.2T, H_{c2}^{ab} (0)=14.7T, and an anisotropy ratio γ=H_{c2}^c (0)/H_{c2}^{ab} (0)=1.2. This anisotropy ratio is similar to the previous results obtained from resistivity measurements on highly textured MgB_2 crystallites[4] or pulsed laser deposited MgB_2 films,[5–6] but is somewhat lower than the reported values of 2.6–3 determined from resistivity on single crystalline MgB_2.[7–8]

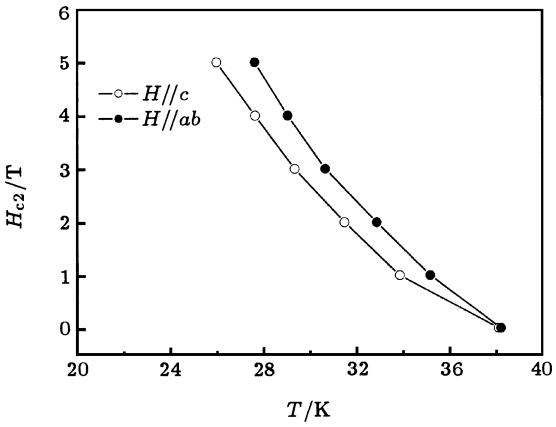


Fig.3. Temperature dependence of upper critical field (H_{c2}–T) defined at the onset superconducting temperature in the ρ–T curves.

The $H_c(0)$ values are used to calculate the coherence length (ξ) from the Ginzburg–Landau (GL) relation:

$$\xi_{ab}^2(0) = \varphi_0/2\pi H_{c2}^c(0), \quad (2)$$

and

$$\xi_c(0) = \varphi_0/2\pi H_{c2}^{ab}(0)\xi_{ab}(0), \quad (3)$$

where φ_0=2.07×10^{-7}G·cm^2 is the flux quantum. We then obtain ξ_{ab} (0)=5.2 nm and ξ_c(0)=4.3nm.

In summary, we have successfully synthesized MgB_2 thin films with a c-axis orientation by a combined CVD method and magnesium diffusion. An upward curvature near T_c is observed in the H_{c2}–T curve for the as-formed MgB_2 films. According to the WHH theory and the GL relation, the anisotropy γ=1.2 and the coherence lengths ξ_{ab} (0)=5.2nm and ξ_c(0)=4.3nm are obtained.

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