Cryst. Res. Technol. **39**, No. 1, 50 – 55 (2004) / **DOI** 10.1002/crat.200310148

Magnetoresistance, voltage-current characteristics, and Hall effect measurements of bulk MgB_2 superconductors

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Received 12 March 2003, accepted 16 May 2003

Key words superconductivity, hall effect, transport properties, MgB_2.
PACS 74.10.+v, 74.70.Ad, 74.25.Fy

Bulk MgB_2 samples were prepared from the commercially available powder (Alfa-Aesar). One of the samples was used in measuring the transport properties by the DC four-probe technique while the other was used in measuring Hall effect using the van-der-Pauw configuration. From the transport measurements, we noticed that the R-T curves shift to lower temperatures under applied magnetic field without any observed enlargement of the transition width. T_c gradually decreases from 37 K at zero field to 32 K at B = 1.4 T. Our V-I data were found to obey a power law expression $V \propto I^{\beta(T,\ B)}$. The change of β with temperature and magnetic field was shown and discussed. R_H is positive under positive applied magnetic field. The 1/ R_H linear dependency on T, usually observed in high temperature superconductors, could not be observed in our case.

1 Introduction

The discovery of superconductivity at 39 K in magnesium diboride (MgB_2) [1] has brought an excitement to the area of basic and applied research on superconducting materials. Several studies have already evidenced that MgB_2 has a good potential for applications [2-5] in view of the relatively high values of critical current density ($J_c > 1$ MA / cm^2) and the successful preparation of wires and films.

There are various studies available in the literature about the effect of pressure [6, 7], thermodynamics [4], transport properties at different temperatures and magnetic fields [8, 9], AC losses [10], magneto optical investigation [11], powder-in-tube wires [12], and microwave surface resistance [13] of MgB_2. The results of these studies and other theoretical studies [14-16] can be summarized as follows: MgB_2 has hexagonal crystal structure with normal state resistivity of about 70 μΩ cm at 300 K and transition width less than 1 K at zero magnetic field. Its upper critical field is in the range 16-18 T. London penetration depth ($\lambda(0) \approx 140$ nm), coherence length ($\xi(0) = 2$-13 nm), Ginzburg-Landau parameter ($\kappa = 26$), and electron-phonon coupling strength ($\lambda \sim 1$) were also calculated. The most important conclusion of these studies is the absence of weak links' effect in MgB_2 contrary to high temperature superconductors. Grain boundaries in MgB_2 do not act as weak links which excludes the necessity for texturing to obtain samples of high critical current density.

The unusual behavior of the Hall effect in many high temperature superconductors and in some conventional superconductors in the mixed and normal states has been a persistent problem in understanding the flux motion in superconductors. The sign reversal of the Hall angle below the critical temperature, as compared to the normal state, is in contrast to traditional models for the vortex Hall effect and is regarded as a fundamental problem of vortex dynamics. Experiments revealed that the Hall anomaly in high temperature

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superconductors observed in moderate magnetic fields, becomes more prominent in smaller magnetic fields and attains its maximum within the vortex liquid and thermodynamic fluctuation range [17, 18]. At temperatures higher than T_c , a rapid drop of the Hall resistivity precedes its sign reversal [19]. The occurrence of the Hall anomaly appears to be connected with the carrier concentration [20], being absent in heavily overdoped cuprates.

Hall effect of MgB_2 has been studied. But, up till now, there are only three reports available in the literature; two of them about thin films [21, 22] and the third is dealing with polycrystalline sample [23]. They agree with the fact that the normal state Hall coefficient R_H is positive, therefore the charge carriers in their samples were holes having a density of $1.7 - 2.8 \times 10^{23}$ holes / cm^3 at 300 K. The three reports disagree on whether the Hall coefficient in the normal state increases or decreases with temperature. In one of the films [21], we can notice a peak just above the transition. In the other film [22], a sign reversal of R_H is noticed in the mixed state. To enrich the information available about MgB_2, we present detailed measurements of Hall effect in bulk samples together with the magnetoresistance and voltage-current characteristics.

2 Experimental

Two bulk sintered MgB_2 samples, prepared from the commercially available powder (Alfa-Aesar), were used in this work. After grinding the powder (using an agate mortar) for 1 hour in Ar environment (using polymer dry box obtained from COY LABS), it was pressed into square-shaped pellets of 1 cm^2 surface area and 3mm thickness under approximately 30 MPa pressure. The pellets were encapsulated in a sealed stainless steel tube after which they were heat treated at 950 °C for 3 hours in a tube furnace under flowing Ar. The samples were then furnace cooled to room temperature in 12 hours.

One of the samples was used in measuring the transport properties using the DC four-probe technique. Silver paste was used to fix four parallel linear probes with 1-2 mm spacing on the surface of the bulk sample for the electrical measurements. The other sample was used in measuring Hall effect using the van-der-Pauw configuration. Four contacts at the corners of the sample were fixed on the top surface using silver paste. Each bulk sample and the connection leads were firmly fixed in a separate sample holder to avoid mechanical stresses during the measurements.

Electrical measurements were achieved using Lake Shore 7507 Hall-effect measurements system. To measure the transport resistance, constant current pulses of 100 mA were applied in two directions to the outer probes of the first sample with a current source (Keithley 220) and the voltage drops were measured through the inner probes with a nanovoltmeter (Keithley 2182) and averaged. Voltage-current characteristics were also measured at different temperatures and magnetic fields in the current range 0-100 mA. Hall-effect data were collected using an IEEE computer interface and IDEAS software provided by Lake Shore. The samples were cooled in a closed cycle cryostat (Advanced Research Systems) and the temperature was controlled using Lake Shore 340 temperature controller. At each temperature the data were collected under different magnetic fields up to 1.4 T, using a 7 inch variable gap electromagnet, applied perpendicular to the current direction.

3 Results and Discussion

Electrical resistances versus temperature (R-T), measured by the standard four-probe method at a DC current of 100 mA, at different magnetic fields (B) (applied perpendicular to the current direction) of the first bulk MgB_2 superconducting sample are shown in fig 1. The inset shows the offset T_c values at different fields obtained from R-T plots. The transition width is less than 1 K, indicating the homogeneity of the sample. The figure indicates also that R-T curves shift to lower temperatures without any observed enlargement of the transition width. This is in contrast to high temperature superconductors, which show a pronounced broadening of resistance with the increasing field, reducing the importance of flux pinning in the mixed state of MgB_2. T_c gradually decreases from 37 K at zero field to 32 K at B = 1.4 T.

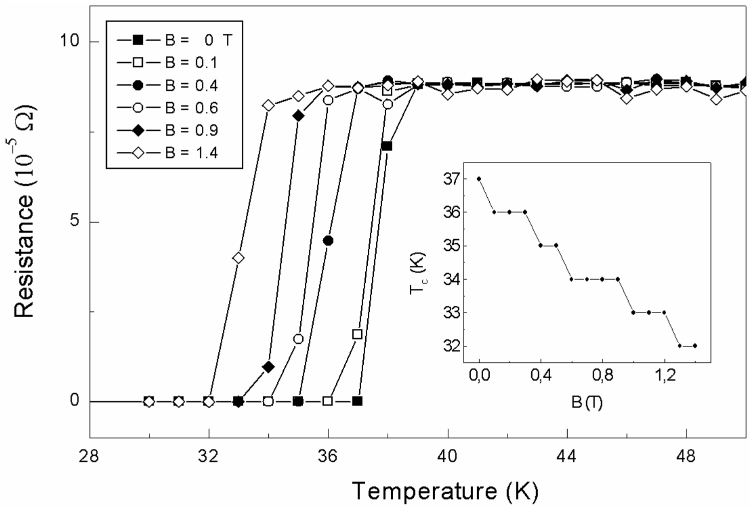

Fig. 1 Electrical resistance versus temperature for MgB$_2$ under different magnetic fields. Inset: Variation of critical temperature T$_c$ with magnetic field.

For high temperature superconductors, the V-I data are found to obey a power law expression $V \propto I^{\beta(T, B)}$ for which the exponential parameter β decreases and approaches unity with increase of temperature (T) and magnetic field (B) [24, 25]. Our V-I data of MgB$_2$ bulk superconductor were fitted to the same expression and the values of β at different temperatures and zero magnetic field are shown in fig 2. At zero field and temperatures less than T$_c$, β has negative values and decreases from -0.15 to -0.35. At the critical temperature, β suddenly increases from -0.35 to +0.75 after which it increases gradually to a value of 2 at 300 K. The inset of fig 2 represents the change of β with magnetic field up to 1.4 T at T = 35 K. For magnetic fields up to 0.5 T, β has negative values and ranges from -0.2 to -0.6. For magnetic fields higher than 0.5 T (which is enough to destroy the superconductivity of the sample at 35 K), β value becomes approximately unity up to 1.4 T.

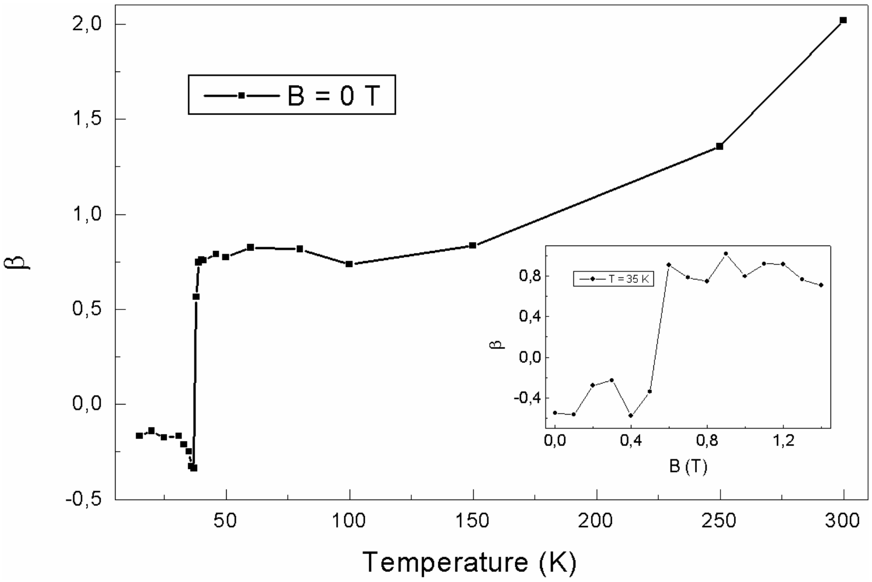

Fig. 2 Variation of β with temperature at zero magnetic field. Inset: Variation of β with magnetic field at 35 K.

The Hall resistivity ρ_{xy} was measured at different temperatures near T$_c$ in the range from 30 to 40 K under different applied magnetic fields up to 1.4 T. The representative curves are shown in fig 3. The resistivity drops from about 1.1×10^{-4} Ω cm to zero in less than 1 K and the curves shift to lower temperatures under application of increased magnetic field. ρ_{xy} was found to be positive for all temperatures and applied magnetic fields (positive or negative). We used it to calculate the Hall coefficient R_H from the relation $R_H = \rho_{xy} / B$.

In fig 4, R_H is plotted against magnetic field at different temperatures near T_c . Both positive and negative fields were applied. Using the relation $R_H = \rho_{xy} / B$, we noticed that R_H is positive under positive applied magnetic field while it becomes negative under negative field. Obviously, this is due to the substitution for positive and negative values of B in the equation. This means that the carriers in MgB_2 are holes in agreement with several reports on MgB_2 [21-23]. Recently, calculations of the band structure of MgB_2 predicted the existence of four sheets in the Fermi surface: one is electronlike and three are holelike [26]. We can also notice from this figure the transition from superconducting to normal state under magnetic field at different temperatures. This can be seen by tracing the change in $|R_H|$ from lower to higher values at certain temperature with changing applied magnetic field. From this we can have an idea about the behavior of MgB_2 in the mixed state.

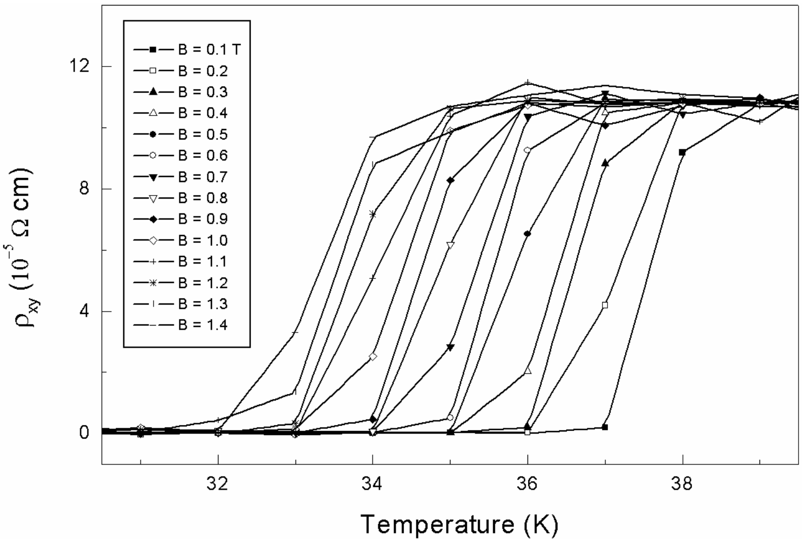

Fig. 3 Hall resistivity ρ_{xy} versus temperature at different magnetic fields for MgB_2.

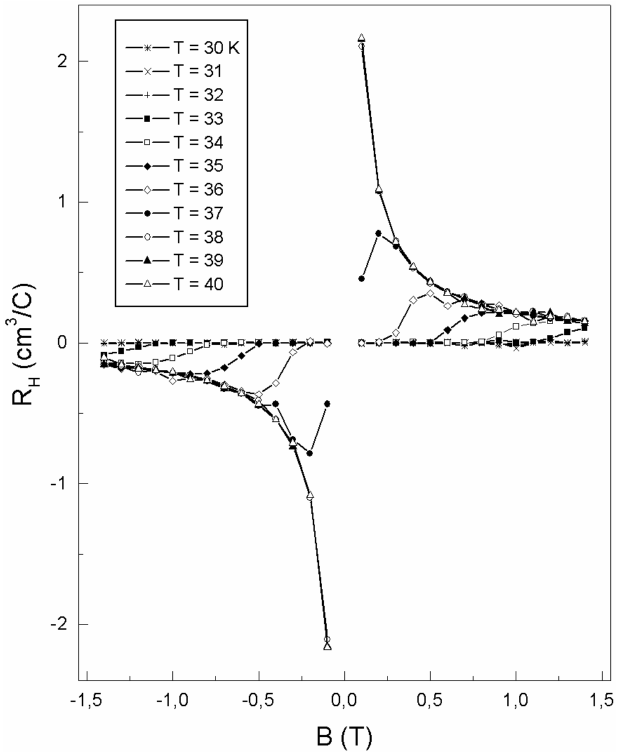

Fig. 4 Hall coefficient R_H versus magnetic field at different temperatures near T_c for MgB_2.

The change of R_H with temperature at different selected magnetic fields is shown in fig 5. R_H increases when the temperature is increased. We see that R_H is strongly temperature dependent at very low magnetic field which is not the case at high magnetic fields. In high temperature superconductors, it was found that $1/R_H$ is linearly dependent on T which is a remarkable and puzzling property. In our case, $1/R_H$ could not be fitted to the linearity relation

$$1/R_H = aT + b,$$

where a and b are constants. It is unclear whether the T-dependent R_H of MgB_2 is caused by multiband effects or is a reflection of an unusual transport mechanism.

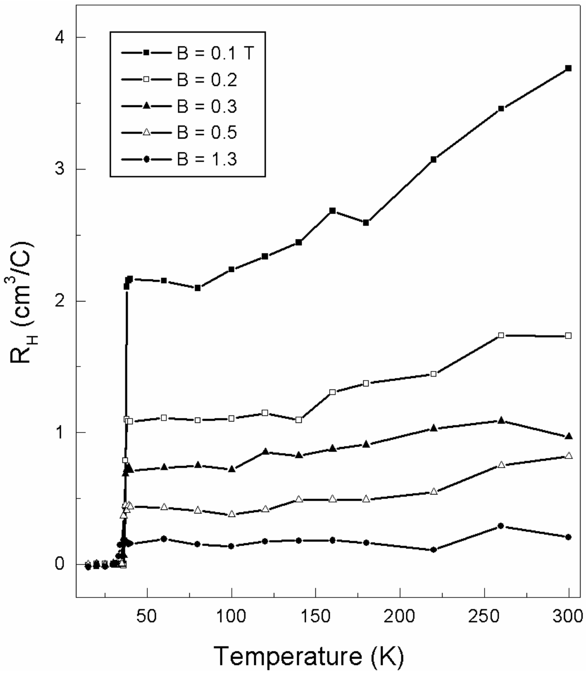

Fig. 5 Variation of the Hall coefficient R_H with temperature at different applied magnetic fields.

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