Abstract.

The upper critical field $H_{c2}(T)$ of sintered pellets of the recently discovered MgB$_2$ superconductor was investigated by transport, ac susceptibility and dc magnetization measurements in magnetic fields up to 16 T covering a temperature range between $T_c \sim 39$ K and $T = 3$ K. The $H_{c2}$ data from ac susceptibility are consistent with resistance data and represent the upper critical field of the major fraction of the investigated sample which increases up to $H_{c2}(0) = 13$ T at $T = 0$ corresponding to a coherence length of $\xi_0 = 5.0$ nm. A small fraction of the sample exhibits higher upper critical fields which were measured both resistively and by dc magnetization measurements. The temperature dependence of the upper critical field, $H_{c2}(T)$, shows a positive curvature near $T_c$ and at intermediate temperatures indicating that MgB$_2$ is in the clean limit. The $H_{c2}(T)$ dependence can be described within a broad temperature region $0.3T_c < T \leq T_c$ by a simple empirical expression $H_{c2}(T) \propto (1-T/T_c)^{1+\alpha}$, where the parameter $\alpha$ specifies the positive curvature of $H_{c2}(T)$. This positive curvature of $H_{c2}(T)$ is similar to that found for the borocarbides YNi$_2$B$_2$C and LuNi$_2$B$_2$C.

The recent discovery of superconductivity in MgB$_2$ [1] at temperatures as high as 40 K has stimulated considerable interest in this system. MgB$_2$, which has a hexagonal AlB$_2$ structure, is a type II-superconductor. A significant boron isotope effect was observed [2] which is an indication for electron-phonon mediated superconductivity in this compound. Magnetic parameters as the Ginsburg-Landau parameter $\kappa = 26$ [3] and the temperature dependence of the upper critical field $H_{c2}(T)$ [3-6] were determined from transport and magnetization measurements [3-7]. So far, a complete $H_{c2}(T)$ curve was reported for a MgB$_2$ wire sample showing a high residual resistivity ratio of about 25 [7].

In the present paper, the temperature dependence of the upper critical field of a sintered MgB$_2$ pellet was studied in magnetic fields up to 16 T in order to analyse the shape of $H_{c2}(T)$ in the whole temperature range for a sample with a moderate residual resistivity ratio. Polycrystalline samples of MgB$_2$ were prepared by a conventional solid state reaction. A stoichiometric mixture of Mg and B was pressed into pellets. These pellets were wrapped in a Ta foil and sealed in a quartz vial. The samples were sintered at 950°C for two hours. Electrical resistance and the superconducting transition of a sample 5 mm in length with a cross-section of about 1 mm$^2$ (cut from the initially prepared pellet) were investigated in magnetic fields up to 16 T using the standard four probe method and current densities between 0.2 and 1 A/cm$^2$. AC susceptibility and dc magnetization measurements were performed on other pieces from the same pellet in magnetic fields up to 9 T and 5 T, respectively.

In Fig. 1a, the temperature dependence of the electrical resistance of the investigated sample is shown. The resistivity at 40 K and 300 K are about 6.4 $\mu \Omega$cm and 29 $\mu \Omega$cm, respectively, resulting in a residual resistivity ratio (RRR) of approximately 4.5. The midpoint value of the normal-state resistivity of the superconducting transition at zero-magnetic field is 38.8 K. A similar $T_c$ value of $T_c=39.0$ K was determined from ac susceptibility data using the onset temperature of the superconducting transition (see Fig. 1b). The field dependence of the electrical resistance of the same sample is shown in Fig. 2 for several temperatures between 36 and 2.9 K. A considerable broadening of the transition curves is observed at low temperatures which may be caused by flux-flow effects at high magnetic fields. The transition widths gradually broaden from 0.2 T at 36 K to 4.5 T at 12 K. A corresponding broadening is found also for resistance-vs.-temperature transition curves at high magnetic fields. In order to compare the transition widths of the two sets of transition curves, the field values $H_{10}$, $H_{50}$ and $H_{90}$ defined at 10%,
50% and 90% of the normal-state resistance are plotted in Fig. 3 as function of the temperature. It is clearly seen that the two data sets determined from field- and from temperature-dependent measurements coincide. Additionally, Fig. 3 shows upper critical field data determined from dc magnetization and from ac susceptibility measurements. The onset of superconductivity was used to define $H_{c2}$ from ac susceptibility. An example for the determination of $H_{c2}$ from dc magnetization is shown in Fig. 4, where magnetization data are plotted for two temperatures in an expanded view. The large resolution allows to visualize not only $H_{c2}$, but also the irreversibility field $H_{irr}$ and a large region between $H_{c2}$ and $H_{irr}$ in which the change of magnetization is reversible. The comparison of the upper critical fields obtained from dc magnetization, ac susceptibility and resistance measurements in Fig. 3 shows clearly, that $H_{c2}^{mag}$ ($H_{c2}$ from magnetization) coincides with $H_{irr}$, whereas $H_{c2}^{sus}$ ($H_{c2}$ from susceptibility) agrees approximately with $H_{10}$. The difference between $H_{c2}^{mag}$ and $H_{c2}^{sus}$ can be explained by the inhomogeneity of the sample. It seems that the major part of the sample has the reduced upper critical fields measured by ac susceptibility, whereas only a relatively small fraction of the sample shows higher $H_{c2}$ values. One has to take into account that already a narrow current path through the sample with improved parameters is sufficient to produce the observed resistive-transition data. The properties of this small fraction can be detected and systematically investigated by sensitive magnetization measurements. The extrapolation of $H_{10}(T)$ to $T = 0$ yields an upper critical field of $H_{c2}(0) \sim 13$ T for the major fraction of the sample, whereas for the small fraction with improved parameters, $H_{c2}(0) \sim 18$ T is estimated by extrapolation of $H_{irr}(T)$ to $T = 0$. Using these $H_{c2}(0)$ values, the coherence lengths $\xi = [\phi_0/(2\pi H_{c2}(0))]^{0.5}$ are found to be 5.0 nm (major fraction) and 4.2 nm (small fraction).

A peculiarity of the $H_{c2}(T)$ dependence shown in Fig. 3 is its pronounced positive curvature near $T_c$. Such a positive curvature of $H_{c2}(T)$ near $T_c$ is a typical feature observed for the non-magnetic rare-earth nickel borocarbides RNi$_2$B$_2$C ($R$=Y,Lu) and can be explained by taking into account the dispersion of the Fermi velocity using an effective two-band model for superconductors in the clean limit [8]. We conclude that also our MgB$_2$ samples are within the clean limit in spite of the rather moderate RRR value of 4.5.

The $H_{c2}(T)$ curves in Fig 3 can be described, in a wide temperature range $0.3T_c < T < T_c$, by the simple expression

$$H_{c2} = H_{c2}^*(1-T/T_c)\alpha$$

(1)

where $H_{c2}^*$ and $\alpha$ are fitting parameter. Notice that $H_{c2}^*$ differs from the true value of $H_{c2}(0)$ due to the negative curvature of the $H_{c2}$-vs.-$T$ curve observed at low temperatures. The fit curves in Fig. 3 describing the $H_{10}(T)$ and $H_{irr}(T)$ data between 12 K and $T_c$ correspond to values of $\alpha = 0.25$ and $\alpha = 0.32$, respectively. Similar values for the parameter $\alpha$ describing the positive curvature of $H_{c2}(T)$ are known from the rare-earth nickel borocarbides YNi$_2$B$_2$C and LuNi$_2$B$_2$C [9].

It is interesting to note that the $H_{c2}(T)$ curve reported for a high quality MgB$_2$ wire with a RRR value of about 25 showed an almost linear temperature dependence in an extended temperature range: In this case, a positive curvature was observed only in a narrow temperature range near $T_c$. It is also remarkably, that the width of the resistive superconducting transition of this wire at low temperatures is similar to that of our sintered sample. In particular, at $T = 1.5$ K onset and completion of superconductivity (corresponding in our notation approximately to $H_{irr}$ and $H_{10}$, respectively) were reported at 16.2 T and 13 T, respectively.

In conclusion, the upper critical field of MgB$_2$ was investigated in a wide temperature range between 3 K and $T_c$. The onset of the superconducting transition of ac susceptibility measurements was found to agree with $H_{c2}$ data measured resistively at 10% of the normal state resistance and represents the upper critical field of the major fraction of the investigated sample. A small fraction of the sample exhibits higher upper critical fields which were measured both resistively and by sensitive dc magnetization.
measurements. The investigated sample shows a variation of the upper critical field at $T = 0$ between $H_{c2}(0) = 13$ T and about 18 T. The considerable broadening of the resistive transitions at high magnetic fields may be caused partly by the sample inhomogeneity, but it also indicates strong flux-flow effects at high fields. A significant positive curvature observed for $H_{c2}(T)$ in a wide temperature region $0.3T_c < T \leq T_c$ suggest that the investigated MgB$_2$ sample is within the clean limit.

References

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Figure captions

Fig. 1

Temperature dependence of (a) resistance and (b) ac susceptibility of a polycrystalline MgB$_2$ sample in zero applied field.

Fig. 2

Field dependence of the resistance of the MgB$_2$ sample of Fig. 1 for several temperatures between 36 and 2.9 K.

Fig. 3

Temperature dependence of the upper critical field determined from dc magnetization (▼), ac susceptibility (Δ) and resistivity measurements with data from field dependence (●) and temperature dependence (○) determined at 10% ($H_{10}$), 50% ($H_{50}$) and 90% ($H_{90}$) of the normal state resistance. Dotted lines are calculated using Eqn. (1) by fitting $H_{c2}$ and $\alpha$ to the experimental data.

Fig. 4

Expanded view of magnetization vs. applied field for two temperatures. Arrows mark the upper critical field $H_{c2}$ and the irreversibility field $H_{irr}$ for the data measured at $T = 27.5$ K. Arrows are also used to show how the applied field was changed in the different branches of the magnetization loop.
Fig. 1

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Fig. 2

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Fig. 3

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Fig. 4

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