JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 10, No. 7, July 2008, p. 1630 - 1632

Invited paper

Magnetoresistivity and upper critical field in superconductor Mo_3Sb_7

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Magnetotransport data on a single crystal of the superconducting Mo_3Sb_7 are reported for temperatures down to 0.4 K and in magnetic fields up to 12 T. The magnetoresistance data are analyzed in terms of the Ginzburg-Landau fluctuation theory. From the experimental data the upper critical field $H_{c2}(0)$ and Ginzburg-Landau coherent length ξ(0) are determined to be ~ 2.3 T and 12 nm, respectively. The $H_{c2}(0)$ value agrees with that inferred from the Werthamer, Helfand, Hohenberg, and Maki theories for conventional type-II superconductors.

(Received April 1, 2008; accepted June 30, 2008)

Keywords: Magnetoresistivity, Superconductor, Mo_3Sb_7

1. Introduction

Measurements of magnetization and electrical resistivity on a single crystal of Mo_3Sb_7 have indicated superconducting transition in this compound at 2.08 K and have provided the upper critical field $\mu_0H_{c2}(0) \sim 1.7$ T [1]. A similar value of $\mu_0H_{c2}(0)$ was deduced from the Andreev-reflection data by Dmitriev et al. [2]. Furthermore, the latter authors have suggested either s-wave or unconventional pairing symmetry for the superconductivity of Mo_3Sb_7 [3]. However, owing to the fact that both the magnetization and Andreev-reflection experiments were performed only down to 1.8 K, accurate determination of $\mu_0H_{c2}(0)$ is rather limited. The narrow temperature range of these studies (1.7- 2.1 K) would also lead to question about the claimed pairing mechanism of the superconductivity. In this work, we have studied magnetoresistance down to 0.4 K and in magnetic fields μ_0H up to 12 T and then, we have determined the mean-field critical temperatures $T_c(H)$. From obtained data we obtained $\mu_0H_{c2}(0)$ ~2.3 T and the Ginzburg-Landau coherent length ξ(0) ~ 12 nm. We found that the temperature dependence of the resistance can be scaled with help of the Ginzburg-Landau fluctuation theory for three dimensional systems.

2. Experimental details

The data presented in this paper were collected on the same single crystal Mo_3Sb_7, on which the magnetization and electrical resistivity down to 1.8 K were previously measured [1]. The crystal was grown by peritectical reaction between Mo and Sb at high temperatures. Details of preparation have been previously elsewhere [1]. The low-temperature magnetoresistance was performed using the dc-standard technique with a current strength of 10 mA. Magnetic field and temperature are controlled via a cryogenic system Oxford PS 120 (?). The direction of magnetic field was applied orthogonally to that of the current.

3. Results and discussion

In Fig. 1 we show temperature dependence of the resistivity at zero field. Clearly, theresistivity exhibits the first-order transition to the superconducting state at T_c = 2.02 ± 0.1 K. A high-quality of the studied Mo_3Sb_7 crystal may be supported by an narrow width of the phase transition ΔT(90% - 10%) = 0.12 K. In the inset of Fig. 1 we show the data in the normal state. One can see that with increasing temperature up to 40 K the resistivity increases rapidly and is well described by an energy gap function $\rho(T) = \rho_0 + bT + c\,exp(-D/k_BT)$, where ρ0 is the residual resistivity of the normal state, b and c are constants and Δ is an energy gap. The fit to the experimental data (solid line) yield ρ_0 = 95.3(3) $\mu\Omega$cm, b = 8.5x10^{-3} $\mu\Omega$cm/K, c = 22.9(2) $\mu\Omega$cm and Δ = 84(2) K. We may add that an attempt of fitting of the resistivity data to the T^2- or T^5-dependence responsible for electron-electron and electron-phonon scattering, respectively, is failed.

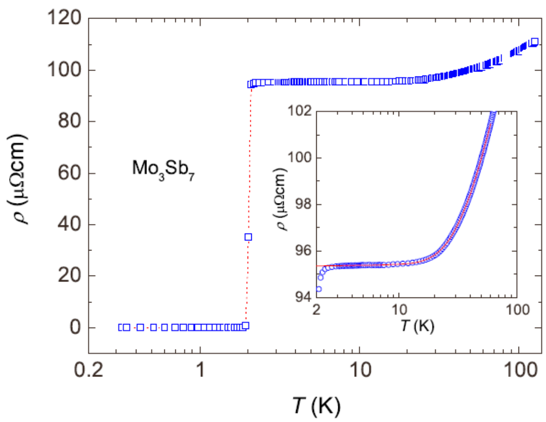

Fig. 1. Temperature dependence of the zero-field electrical resistivity for the Mo_3Sb_7 single crystal. The inset shows the fit describing an energy gap function of the resistivity for the temperature range 3 - 40 K.

In Fig. 2, the resistivity at several applied fields up to 8 T is shown as a function of temperature. Obviously, for increasing applied field there is a suppression of the superconducting phase to lower temperatures. Other feature is seen here is that the field shifts resistivity to higher values. This behaviour resembles that of magnetic field induced superconductor-insulator transition in $Nd_{2-x}Ce_xCuO_{4\pm\delta}$ films [4]. For temperature above 5 K, the values of the resistivity in different fields up to 12 T (not shown here) are practically identical.

Shown in Fig. 3 are temperature dependencies of the resistivity measured in magnetic fields $0\leq \mu_0 H \leq 2$ T. At each field the resistivity curve exhibits a rounding before the superconductivity sets in. Such a feature has previously observed in $YBa_2Cu_3O_{7-\delta}$ and has been attributed to thermodynamic fluctuations of the order parameter [5]. The effect of fluctuations on the transport properties of the type-II superconductors in magnetic fields has studied by several authors [6-8] by means of the time-dependent Ginzburg-Landau theory. Following Ullah and Dorsey [7], who derived expressions for the fluctuation conductivity σ_{fl} for three dimensional (3D) systems:

$$\sigma_{fl}\left(\mu_0 H/T^2\right)^{1/3} = f\left(\frac{T-T_c(H)}{(T\mu_0 H)^{2/3}} \right), \quad (1)$$

where f is the unknown scaling function, we have considered the resistivity data for $0.25\leq \mu_0 H \leq 2$ T. In Fig. 4 we show the dependence of $\sigma_{fl}(\mu_0 H/T^2)^{1/3}$ on $\left(\frac{T-T_c(H)}{(T\mu_0 H)^{2/3}}\right)$. As can be seen from the figure, the 3D scaling behaviour persists for the resistivity in felds up to 1.35 T. The obtained results imply that the fluctuations may be important in the temperature range around T_c.

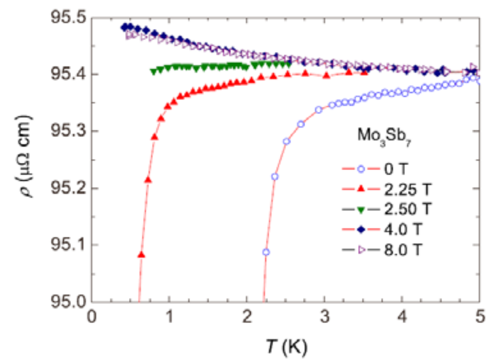

Fig. 2. Electrical resistivity as a function of temperature for the Mo_3Sb_7 single crystal measured in magnetic fields up to 8 T.

The $H_{c2}(T)$ values deduced from the experimental data are shown in Fig. 5. Note that the critical temperature $T_c(H)$ obtained by the above scaling has similar values to those inferred from the maximum of the temperature derivative of the resistivity. We observe that the upper critical field $H_{c2}(T)$ data do not follow the conventional BCS formula for weak-coupling superconductors i.e., $Hc2(T) \sim -(T/T_c)^2$ [9]. Instead, the values of $\mu_0 H_{c2}$ are well described by a power law $\mu_0 H_{c2} = \mu_0 H_{c2}(0)[1 - (T/T_c)^{1.27}]$. From the fitting $\mu_0 H_{c2}$ (0) is determined to be 2.31 T. The upper critical field of a superconductor reflects the combined effect of an external magnetic field on the spin and orbital degrees of freedom of the conduction electrons. Werthamer et al. [10] and Maki [11] developed a theory for H_{c2} taking into account both spin and orbital paramagnetic effects. Using the Werhammer-Helfand-Hohenber (WHH) equation for type-II superconductors in the dirty limit at T = 0 [10]:

$$\mu_0 H_{c2}(0) = 0.693(-d\mu_0 H_{c2}/dT)\Big|_{T\sim T_c} T_c \quad (2)$$

we estimated $\mu_0 H_{c2}(0)$ to be 1.94 T, being considerably smaller than that extrapolated above. The the upper critical field does not behave as predicted WHH formula for the clean limit can also be seen in the inset of Fig. 5, illustrated as dotted line. In the calculation, we used the initial slope of the upper critical field vs temperatures around T_c, $d\mu_0 H_{c2}/dT)\big|_{T\sim T_c}$ = - 1.39 T/K. The initial slope $d\mu_0 H_{c2}/dT)\big|_{T\sim T_c}$ results in a Maki-parameter [11] as α =-0.52758 $d\mu_0 H_{c2}/dT)\big|_{T\sim T_c}$ = 0.733. The upper critical field $\mu_0 H_{c2}$ (0) is calculated as $\mu_0 H_{c2}(0) = \alpha H_{p0}/\sqrt{2}$= 2.19 T, where $H_{p0} = 1{:}84 T_C$ = 4.23T. Thus, the obtained $\mu_0 H_{c2}$ (0) with Werhammer-Helfand-Hohenber-Maki (WHHM) theory reasonably agrees with that extrapolated value of 2.31 T. From the latter value we deduce zero-temperature coherence length $\xi(0)$ of 12 nm, which is rather short as for typical type-II superconductors.

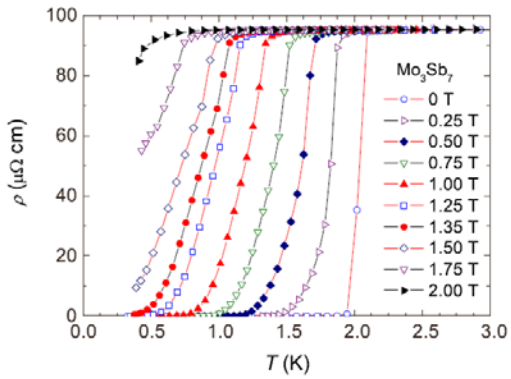

Fig. 3. Electrical resistivity as a function of temperature for the Mo_3Sb_7 single crystal measured in magnetic fields up to 2 T.

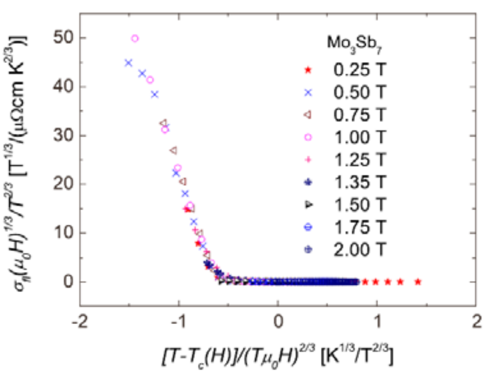

Fig. 4. $\sigma_{fl}(\mu_0 H/T^2)^{1/3}$ *of* Mo_3Sb_7 *as a function of* $\left(\frac{T-T_c(H)}{(T\mu_0 H)^{2/3}}\right)$ *for magnetic fields* $0 \le \mu_0 H \le 2$ *T.*

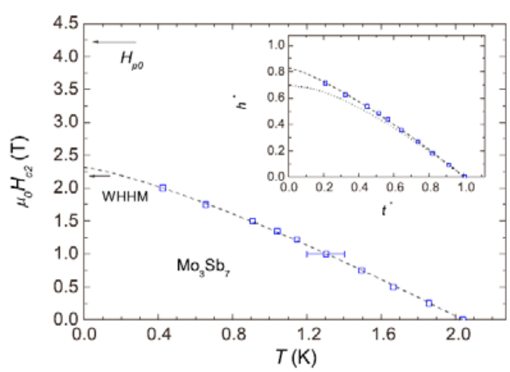

Fig. 5. Magnetic field $\mu_0 H$ *vs temperature T phase diagram of* Mo_3Sb_7. *The dashed line is a fit to power law* $\mu_0 H_{c2} = \mu_0 H_{c2}(0)[1 - (T/T_c)^{1.27}]$. *The arrows indicate the Pauli-limiting field* H_{p0} *and the upper critical field estimated from WHHM theory, respectively. The inset compares WHH theory in the clean limit (dotted line) with the experimental data of* Mo_3Sb_7 *(open squares)…*

4. Conclusions

In this paper we present magnetorestance data on a single crystal of the superconductor Mo_3Sb_7. In the normal state we observe that the resistivity is field-independent up to 12 T. In the superconducting state we find that the fluctuation conductivity follows a 3D scaling behaviour and the upper critical field $\mu_0 H(T)$ curve agrees with the WHHM theory for type-II superconductors with paramagnetic limiting. From the analysis of the magnetoresistance data we deduced the zero-temperature upper critical field $\mu_0 H$ ~2.3 T and zero-temperature coherence length $\xi(0) \sim 12$nm

Acknowledgement

The author V.H.T. would like to thank financial support from the the Ministry of Science and Higher Education under grant No. N202 082 31/0449. The author E.B. acknowledges support from the Austrian FWF, P18054. The author A.G. acknowledges the support of Romanian CEEX projects RP5/2005 and M1-11-98/2006. The measurement of magnetoresistance is made possible due to support from COST Action P16 Emergent Behaviour in Correlated Matter (ECOM).

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