ELSEVIER

Synthetic Metals 135–136 (2003) 721–722

SYNTHETIC METALS

www.elsevier.com/locate/synmet

Magnetic susceptibility and electrical resistivity of a mesoporous carbon CMK-1

M. Kuno [a],[*] T. Naka [a], E. Negishi [a], H. Matsui [a, b], O. Terasaki [a], R. Ryoo [c], N. Toyota [a, b]

[a] Physics Department andb[2] Center for Interdisciplinary Research, Tohoku University, Sendai 980-8578, Japan
[c] National Creative Reserch Intiative Center for Functional Nanomaterials and Department of Chemistry,
Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

Received 2 July 2002; accepted 20 October 2002

Abstract

The magnetic susceptibility of the title material follows a Curie-Weiss law at high temperatures, and a peak of the susceptibility appears around 4 K associated with remarkable hysteresis below 10 K, which is reminescent of a spin-glass behavior. The temperature dependence of the electrical resistivity is proportional to exp ($T^{-1/3}$), which may reveal a two-dimensional variable range hopping.

keywords: magnetic measurements, conductivity, graphite and related compounds

1. Introduction

Mesoporous materials are characterized by periodically arranged cavities or channels with sizes ranging from 2 to 50 nm. Many kinds of mesoporous silica have been synthesized with use of surfactants as a template. Some mesoporous materials have attracted much attentions as containers to synthesize new materials such as a mesoporous carbon [1] and Pt nano-particles [2].

A mesoporous carbon CMK-1 presented here has been synthesized using mesoporous silica MCM-48 as a template [1]. According to an electron crystallography technique [3], the structure of MCM-48 is well explained by a gyroid surface, which is one of a periodic minimal surface belonging to a cubic space group symmetry of $Ia\bar{3}d$. The amorphous silica forms a wall exactly following a gyroid surface with thickness of ca. 1.3 nm. Furthermore, the wall separates the structure into two enantiomeric channel systems, which are not interconnected with each other. The synthesis of CMK-1 employs a carbonization of sucrose inside the channels of MCM-48. Then the CMK-1 almost reflects the structure of the channels of MCM-48 and never loses periodicity over the mesoscopic scale essentially [4]. On an atomic scale, however, any periodic arrangements have never been identified by X-ray diffractions. Thus we expect that the wall could consist of amorphous carbon atoms, whereas the detailed structure in CMK-1 is still controversial. In addition, its solid-state properties have not been studied yet at all. Here we report, for the first time, on the magnetic susceptibility and the electrical resistivity.

2. Experimental

The original CMK-1 is a fine powder, the average diameter of which is about 1 μm. The magnetic susceptibility measurements have been performed by a commercial SQUID magnetometer (Quantum Design, Inc.) with the powdery samples sealed inside a quartz tube. For the dc electrical resistivity measurements by a four probe method, we have used the platy samples with a diameter 6 mm sintered at 300 °C for 2 hours, which is determined by thermogravimetric measurements.

3. Results and Discussions

Figure 1 shows the temperature dependence of the magnetic susceptibilities, χ. The data for the zero field cool and for the field cool at 300 Oe are denoted by χ_{ZFC} (solid circles) and χ_{FC} (open circles), respectively. The both χ_{ZFC} and χ_{FC}, which are reversible above 10 K, are fitted for several external magnetic fields using the Curie-Weiss law

---

[*] Corresponding author. Tel: +81-22-217-6604; fax: +81-22-217-6786; E-mail: kuno@ldp.phys.tohoku.ac.jp

0379-6779/03/$ – see front matter
doi:10.1016/S0379-6779(02)00812-3

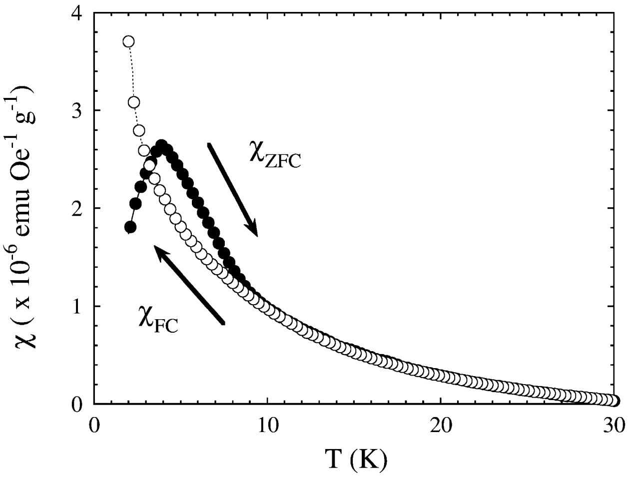

Fig. 1 Temperature dependence of the magnetic susceptibilities. Solid and open circles indicate the data in χ_{ZFC} and χ_{FC}, respectively.

with diamagnetic component, χ_{dia}. The average Curie constant and Weiss temperature are evaluated to be 1.8 x 10^{-5} K·emu·g^{-1} and -2 K, and χ_{dia} is about -5 x 10^{-7} emu·Oe^{-1}·g^{-1}. From the Curie constant, the spin density is obtained as 3.0 x 10^{19} g^{-1}, with assumptions of S = 1/2 and g = 2. To note, the value is very close to 2.8 x 10^{19} g^{-1} in nano-graphite [5]. The negative Weiss temperature implies that antiferromagnetic interactions exist in the present system. Below 10 K, χ_{FC} continuously increases down to 2 K, whereas χ_{ZFC} exhibits a peak around 4 K. The difference suggests an emergence of a spin glass as observed in activated carbon nano-fibers [6]. The wall of CMK-1 might be composed of amorphous carbons, which yield dangling bonds to introduce a spin.

The temperature dependence of the dc electrical resistivity ρ is shown in Fig. 2. With decreasing temperature down to 0.5 K, the resistivity increases by 6 orders of magnitude. The resistivity, however, is never explained by a thermal activation type observed in usual semiconductors. The inset plots ln[lnρ] versus ln$T$. Below 60 K, the data is in good agreements with the solid line, which follows exp ($T^{-1/3}$). Above 60 K, ρ has T^{-2} dependence, the origin of which is not clear. In a model of a variable range hopping (VRH) [7], the resistivity is described by

$$\rho = \rho_0 \exp\left(T_0/T\right)^{1/(d+1)}, \quad (1)$$

where d represents a dimension of a given electronic system. According to Eq. (1) and the solid line in the inset, d is estimated to be about 2. Consequently, the present results strongly suggest that the electrical resistivity below 60 K is attributed to a two-dimensional VRH. The two-dimensional conduction might be attributed to curved surfaces of the wall. The surface is so strongly bent that there may be a considerably large number of defects and dangling bonds on the surface, which causes the VRH. In the case of a carbon nano-tube, a model has been introduced to explain the observed VRH [8]. The model consists of metallic islands and energy barriers; the latter is derived from defects and intertube connections. From the model, the VRH of a carbon nano-tube is originated by the hopping conductions between the metallic islands crossing the energy barriers. Similar model might be also applied to the present CMK-1. Further investigations are necessary to check the model. Finally, we point out that the present two-dimensional VRH might be associated with the spin glass behavior mentioned above.

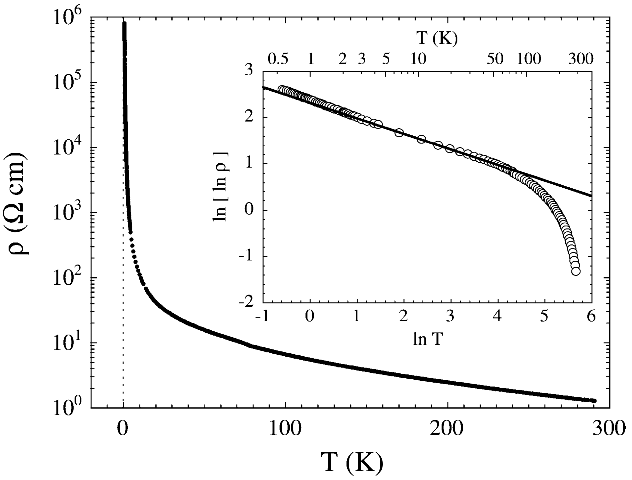

Fig. 2 Temperature dependence of the dc electrical resistivity. Inset shows a plot of ln[lnρ] vs. ln$T$.

References

[1] S. H. Joo, S. Jun, R. Ryoo, Microporous and Mesoporous Materials 44-45 (2001) 153.

[2] S. H. Joo, S. J. Choi, I. Oh, J. Kwak, Z. Liu, O. Terasaki, R. Ryoo, Nature 412 (2001) 169.

[3] A. Carlsson, M. Kaneda, Y. Sakamoto, O. Terasaki, R. Ryoo, S. H. Joo, J. Electron Microscopy 48 (1999) 795.

[4] M. Kaneda, T. Tsubakiyama, A. Carlsson, Y. Sakamoto, T. Ohsuna, O. Terasaki, S. H. Joo, R. Ryoo, J. Phys. Chem. B 106 (2002) 1256.

[5] A. Nakayama, K. Suzuki, T. Enoki, S. L. di Vittorio, M. S. Dresselhaus, K. Koga, M. Endo, N. Shindo, Synth. Metals 57 (1993) 3736.

[6] Y. Shibayama, H. Sato, T. Enoki, M. Endo, Phys. Rev. Lett. 84 (1999) 1744.

[7] N. F. Mott, E. A. Davis, Electronic Process in Non-Crystalline Materials, Clarendon, Oxford, 1979.

[8] A. B. Kaiser, G. Dusberg, S. Roth, Phys. Rev. B 57 (1998) 1418.