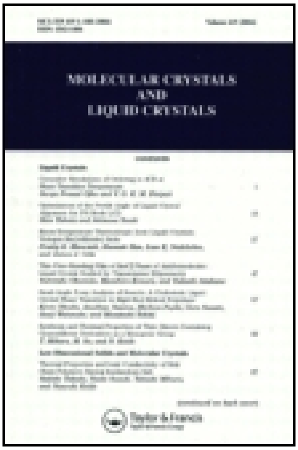
This article was downloaded by: [University of Haifa Library]
On: 16 August 2012, At: 12:28
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954
Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Two-Dimensional Weak Localization Effect in Stage-4 $MoCl_5$ Graphite Intercalation Compound

Masatsugu Suzuki [a], Itsuko S. Suzuki [a], Keiko Matsubara [b] & Ko Sugihara [c]

[a] Department of Physics, State University of New York at Binghamton, Binghamton, New York, 13902-6016, USA

[b] Department of Electrical Engineering, College of Science and Technology, Nihon University, Chiyoda-ku, Tokyo, 101, JAPAN

[c] College of Pharmacy, Nihon University, Funabashi, Chiba, 274, JAPAN

Version of record first published: 24 Sep 2006

To cite this article: Masatsugu Suzuki, Itsuko S. Suzuki, Keiko Matsubara & Ko Sugihara (2000): Two-Dimensional Weak Localization Effect in Stage-4 $MoCl_5$ Graphite Intercalation Compound, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 340:1, 217-222

To link to this article: http://dx.doi.org/10.1080/10587250008025469

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Mol. Cryst. and Liq. Cryst., 2000, Vol. 340, pp. 217-222
Reprints available directly from the publisher
Photocopying permitted by license only

© 2000 OPA (Overseas Publishers Association) N.V.
Published by license under the
Gordon and Breach Science Publishers imprint.
Printed in Malaysia

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

Two-Dimensional Weak Localization Effect in Stage-4 $MoCl_5$ Graphite Intercalation Compound

MASATSUGU SUZUKI[a], ITSUKO S. SUZUKI[a],
KEIKO MATSUBARA[b] and KO SUGIHARA[c]

[a]*Department of Physics, State University of New York at Binghamton, Binghamton, New York 13902–6016, USA*, [b]*Department of Electrical Engineering, College of Science and Technology, Nihon University, Chiyoda-ku, Tokyo 101, JAPAN and* [c]*College of Pharmacy, Nihon University, Funabashi, Chiba 274, JAPAN*

The c-axis resistivity $\rho_c(H, T)$ of stage-4 $MoCl_5$ GIC between 1.9 and 50 K has been measured with and without an external magnetic field along the c axis ($0 \leq H \leq 44$ kOe). The interior G layers form a bottleneck to the c-axis conduction. The T and H dependence of ρ_c is mainly determined from that of the bottleneck resistivity proportional to the in-plane resistivity of interior graphite layers. A logarithmic behavior of ρ_c in the form of In(T) and In(H) indicates that the two-dimensional weak localization occurs in the interior graphite layers. The T and H dependence of the in-plane conductivity derived from ρ_c is discussed in terms of scaling relation predicted from the theory of two-dimensional weak localization.

Keywords: weak localization; negative magnetoresistance; graphite intercalation compounds

INTRODUCTION

In a previous paper [1], we have reported the temperature (T) dependence of the c-axis resistivity (ρ_c) for stage-2 to 6 $MoCl_5$ GICs in the presence of an

+ Present address: Energy Laboratory, Electronic Research Center, Samsung Yokohama Research Institute, 2-7, Sugasawa-cho, Tsurumi-ku, Yokohama 230-0027, JAPAN

external magnetic field H along the c axis. We have found (i) a metallic behavior in stage 2, (ii) a logarithmic behavior at low T in stage 3 and 4, and a negative magnetoresistance (n-MR) at low T and weak H in stage 3 to 5, and (iii) a semiconductor-like behavior in high stages (5, 6). We have shown that these results can be qualitatively explained within the framework of a two-dimensional (2D) band model with hopping conduction mechanism. The logarithmic behavior and negative magnetoresistance are due to a 2D weak localization effect (WLE) occurring in the interior graphite (G) layers [2]. In this paper we have undertaken an extensive study on the T dependence and H dependence of ρ_c for stage-4 $MoCl_5$ GIC, where the magnetic field is applied along the c axis. These results are discussed in the light of the theories on 2D WLE.

EXPERIMENTAL PROCEDURE

The c-axis resistivity ρ_c was measured using a system of SQUID magnetometer (Quantum Design, MPMS XL-5) with an external device control and an ultra low field capability option. Before setting up a sample at 298 K, a remanent magnetic field in a superconducting magnet was reduced to one less than 3 mOe using an ultra low field capability option. For convenience, hereafter this remanent field is noted as the state of H = 0. The sample was cooled down to 1.9 K for typically 8 hours for a annealed case and 0.5 hours for a quenched case. Then the c-axis resistivity was measured with increasing T from 1.9 to 50 K with and without H along the c axis.

RESULT

The value of ρ_c for the quenched system is relatively larger than that for the annealed system for the same T and H, reflecting the nature of disordered state in graphite layers. Figures 1(a) and (b) show the T dependence of ρ_c for the annealed system in the presence of H along the c axis. Similar behavior is observed for the quenched system. Figure 2 shows the H dependence of T_{min} for both the annealed and quenched systems. The temperature T_{min} decreases with increasing H at low H, exhibiting a local minimum around H = 2 kOe, and increases with further increasing H: T_{min} = 46 K at H = 20 kOe.

In order to analyze the T dependence of ρ_c in the presence of H, we assume that the resistivity is described by

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

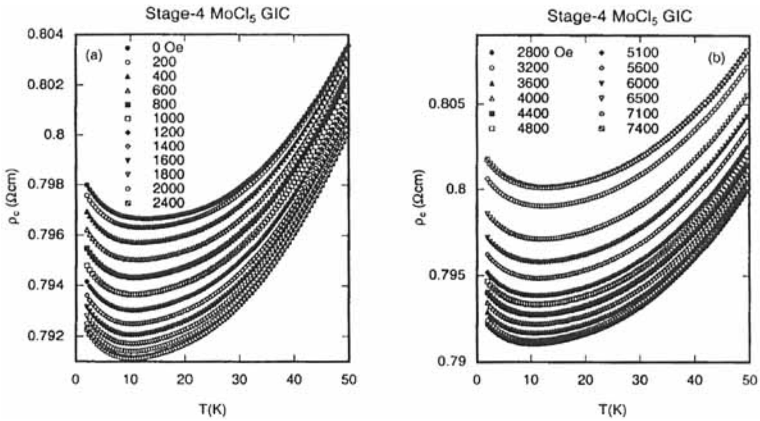


FIGURE 1 (a) and (b) T dependence of ρ_c with various H for stage-4 $MoCl_5$ GIC in the annealed system. H // c.

$$\rho_c = \rho_0 - \rho_1 \ln(T) + \rho_2 T + \rho_3 T^2 \quad (1)$$

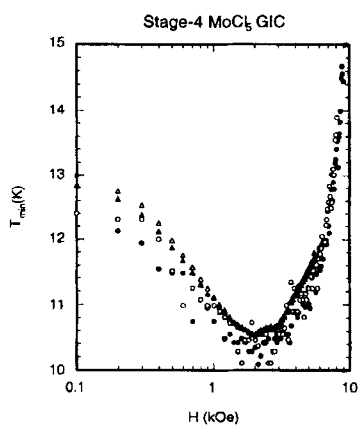


FIGURE 2 H dependence of T_{min}. Experimental values of T_{min} for the annealed system (●) and the quenched system (○). Calculated values of T_{min} for the annealed system (▲) and for the quenched system (△).

where ρ_0, ρ_1, ρ_2, and ρ_3 are positive constants dependent on H, the second logarithmic term is due to the 2D WLE, and the third and fourth terms are due to the scattering of carriers by phonons. The value of T_{min} can be calculated from $d\rho_c/dT = 0$.

We find that the data of ρ_c vs T with 1.9≤T≤25 K for both the annealed and quenched systems can be well described by Eq.(1) for each H below 5.6 kOe. The parameters ρ_1 to ρ_4 for each H are determined by the least squares fit of the data to Eq.(1): for example, ρ_0 = 0.79869± 0.00001 Ωcm, ρ_1

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

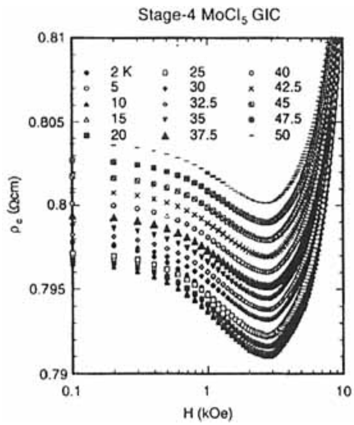


FIGURE 3 H dependence of ρ_c for stage-4 $MoCl_5$ GIC in the annealed system at various T. H // c.

= (1.038 ± 0.024) x 10^{-3} Ωcm, ρ_2 = (1.863 ± 0.534) x 10^{-5} Ωcm K^{-1}, and ρ_3 = (2.269 ± 0.120) x 10^{-6} Ωcm K^{-2} at H = 0 for the annealed system. In Fig.2 we also show the calculated values of T_{min} for both the annealed and quenched systems. The experimental data of T_{min} vs H are in good agreement with the calculated ones.

The ratio ρ_1/ρ_0 tends to increase slightly with increasing H: ρ_1/ρ_0 = 0.0013 at H = 0 to 0.00138 at H = 5.6 kOe for the annealed system. In the previous paper [1] we have shown that the following relation is valid in stage-4 $MoCl_5$ GIC: $\rho_1/\rho_0 = (e^2/2\pi^2\hbar\, \sigma_{2D}^0)(\alpha p+\gamma)$. Note that σ_{2D}^0 (= 1.0776 x 10^{-2} Ω^{-1}) corresponds to the in-plane conductivity defined by I_c/ρ_a^0, where ρ_a^0 (= 18 μΩcm at 4.2 K) [3] is the in-plane resistivity and I_c (= 19.396 ± 0.014 Å) is the c-axis repeat distance for stage-4 $MoCl_5$ GIC. Using the ratio ρ_1/ρ_0 = 1.30 x 10^{-3} the constant ($\alpha p + \gamma$) can be estimated as 1.14, which is comparable with 0.90 in the previous paper [1].

Figure 3 shows the H dependence of ρ_c with 1.9≤T≤50 K for the annealed system. For each T ρ_c decreases with increasing H at low H, exhibits a local minimum around H = 2.5 kOe, and ρ_c increases with further increasing H. The sign of the difference $\Delta\rho_c$ [$=\rho_c(T,H) - \rho_c(T,H=0)$] is negative for 0≤H≤6 - 7 kOe due to the 2D WLE. Because of the Boltzmann term σ_B^{2D} which may drastically decrease with increasing H above 6 - 7 kOe the sign of $\Delta\rho_c$ becomes positive. For 0.6≤H≤2.0 kOe the H dependence of ρ_c is described by a logarithmic term [$\rho_c = b_1 - b_2 \ln(H)$], due to the 2D WLE. The ratio b_1/b_0 is dependent on T. It decreases with increasing T: b_1/b_0 = (3.93 ± 0.05) x 10^{-3} at 1.9 K and (2.14 ± 0.05) x 10^{-3} at 50 K.

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

Downloaded by [University of Haifa Library] at 12:28 16 August 2012

DISCUSSION

We assume that the c-axis resistivity of stage-4 $MoCl_5$ GIC is proportional to the in-plane resistivity tensor of the interior G layers (ρ_{xx}), where $\rho_{xx} = A\rho_c$ and A is constant. Then the correction term of the conductivity tensor (X) in the interior G layers can be expressed by

$$X = \frac{\Delta\sigma(T,H)}{\sigma(T,H=0)} = \frac{\rho_c(T,H=0)}{\rho_c(T,H)} \frac{1}{1+\dfrac{\lambda^2 H^2}{[\rho_c(T,H)]^2}} - 1, \qquad (2)$$

where $\lambda = R_H / A$ and R_H is the Hall coefficient defined by $R_H = 1/nec = 6.25 \times 10^{10} / n$. The carrier density n for stage-4 $MoCl_5$ GIC is related to N_{2D} by $n = N_{2D} / I_c (= 5.16 \times 10^{20}/cm^3)$, where N_{2D} is typically $10^{14}/cm^2$ for the 2D band model [4]. Using the value of A $(= \rho_a/\rho_c = 18\ \mu\Omega cm/0.8\ \Omega cm = 2.25 \times 10^{-5})$ [3], we have $\lambda = 6.25 \times 10^{10}/An = 5.39 \times 10^{-6}$.

The value of λ for stage-4 $MoCl_5$ GIC can be determined as follows. First we calculate the H dependence of X for $1.9 \le T \le 50$ K when the parameter λ is changed between $\lambda = 2 \times 10^{-6}$ and 2×10^{-5} around the expected value $\lambda = 5.39 \times 10^{-6}$. For each λ we find that the H dependence of X at T = 2.0 K in the limited

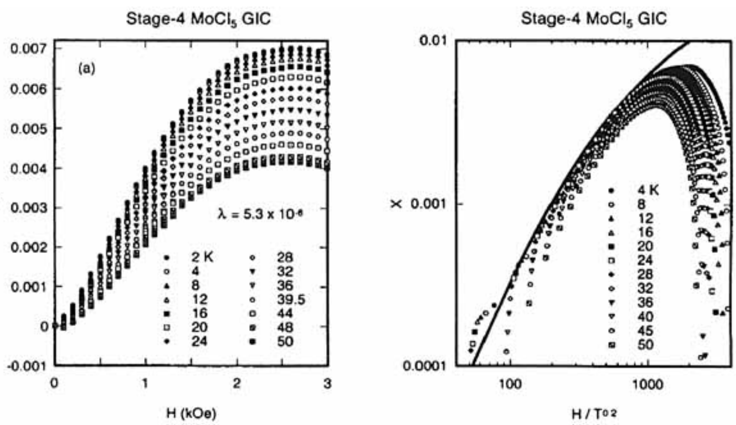


FIGURE 4 (a) H dependence of the conductivity X with $\lambda = 5.3 \times 10^{-6}$ for various T. (b) Scaling plot of X with $\lambda = 5.3 \times 10^{-6}$ as a function of H/T^p (p = 0.2) for various T. The solid line is described in the text.

field range between 0.5 kOe and 2 kOe can be well fitted to a logarithmic form defined by $c_1 + c_2 \ln(H)$. Then we make a plot of c_2 as a function of λ. The value of c_2 linearly decreases with λ for $3 \times 10^{-6} \leq \lambda \leq 7 \times 10^{-6}$: $c_2 = 0.00413 - 37.65\lambda$. An appropriate value of λ (= 5.30×10^{-6}) is chosen under the condition that c_2 coincides with the value of b_1/b_0 (= 3.93 ± 0.05) x 10^{-3} at 1.9 K. This value of λ is very close to the expected value of λ (= 5.39×10^{-6}).

Figure 4(a) shows the H dependence of X with $\lambda = 5.30 \times 10^{-6}$ at various T. The value of X is positive at least below 7 - 8 kOe and has a peak around H = 2.6 - 2.7 kOe, which are independent of T for $1.9 \leq T \leq 50$ K. For any fixed H the value of X decreases with increasing T. Figure 4(b) shows the log-log plot of X with $\lambda = 5.30 \times 10^{-6}$ as a function of H/T^p with p = 0.2, where p is the exponent of relaxation time for inelastic scattering τ_ε: $\tau_\varepsilon \approx T^{-p}$.

Here we discuss the H and T dependence of X in terms of the theory of 2D WLE. The conductivity is predicted to be expressed by a scaling function $f(H/H_\varepsilon)$, where $f(x) = \ln(1/x) - \Psi(1/2 + 1/x)$, $\Psi(x)$ is a digamma function, and H_ε is proportional to $1/\tau_\varepsilon$. As shown in Fig.4(b) it seems that almost all the data of X with $\lambda = 5.3 \times 10^{-6}$ for T<34 K fall on the solid line described by a scaling function $X = -B f(H/H_e)$ for $H/T^{0.2}<800$ where B= 0.0074 and $H_\varepsilon = \beta T^p$ with p = 0.20 ± 0.02 and $\beta = 90$. For $H/T^{0.2} >> 800$ the data of X greatly deviate from this scaling function partly because of the 2D Boltzmann term σ_B^{2D}.

References

[1] M. Suzuki, C. Lee, I.S. Suzuki, K. Matsubara, and K. Sugihara, Phys. Rev. B **54,** 17128 (1996).

[2] K. Sugihara, K. Matsubara, I.S. Suzuki, and M. Suzuki, J. Phys. Soc. Jpn. **67,** 4169 (1998).

[3] K. Matsubara, K. Sugihara, I.S. Suzuki, and M. Suzuki, J. Phys. Condensed Matter **11,** 3149 (1999).

[4] L. Piraux, V. Bayot, X. Gonze, J.-P. Michenaud, and J.-P. Issi, Phys. Rev. B **36,** 9045 (1987).

Downloaded by [University of Haifa Library] at 12:28 16 August 2012