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Magnetoresistance of amorphous indium oxide films at the region of weak–strong localization crossover

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Abstract

The magnetoresistance (MR) was measured in films of amorphous indium oxide at the region of weak–strong localization crossover (WSLC). The change from positive to negative MR was observed commonly in the samples as temperature increased, passing through 8–10 K, which falls within the WSLC region of each sample. The observed MR is fitted to a formula composed of the intrastate interaction and the delocalization (DL) terms. The fitting results show that the intrastate interaction term remains up to the high limit of the WSLC region, above which the weak localization is valid, while the DL effect is evident down to the low limit of the WSLC region, below which the strong localization prevails. Temperature dependences of the fitting parameters show qualitative agreement with theoretical expectations.

1. Introduction

According to a scaling theory of localization [1] electrons in a disordered two-dimensional system are, in principle, always localized. At a finite temperature localization is rather weak due to thermal energy, which helps electrons to move beyond their local confinements to a large extent. As a consequence the resistance of a two-dimensional system [2] has a logarithmic dependence on the temperature (weakly localized regime). The resistance increases with decreasing temperature and finally reaches a critical value $R_c \sim h/e^2 \sim (26\ \mathrm{k}\Omega)$ at a certain point, below which the increase in resistance becomes exponential (strongly localized regime). Thus, in a two-dimensional system, the weak–strong localization crossover (WSLC) is expected to occur as the temperature decreases passing through a certain temperature (or temperature range).

Various effects of a magnetic field on resistance have been developed theoretically in both the weakly localized and the strongly localized regime. In the weakly localized regime delocalization (DL) [3] gives rise to a negative magnetoresistance (MR) while the enhanced electron–electron interaction effects [4] lead to mostly positive MR (PMR) through Zeeman spin splitting and the orbital effect. A magnetic field destroys the constructive interference between backscattered electron waves and, thus, reduces the resistance due to

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the localization effect. It is well known, however, that the spin–orbit scattering and the superconducting fluctuation effects reduce DL in the presence of a magnetic field [5]. In the strongly localized regime, on the other hand, the quantum interference [6] gives rise to a negative MR (NMR), while other effects such as the wavefunction shrinking [7] and the intrastate interaction [8] lead to PMRs.

Most experimental observations related to the MR in two-dimensional systems have been focused either on the weakly localized regime or on the strongly localized regime where the variable-range hopping (VRH) is valid. Reports at (or near) the WSLC region are rarely found, probably because of little understanding in theory and, thus, of the difficulty of explaining the observed MR. The only report on the MR at WSLC, as far as we know, is in films of novel metal–Ge composites [9]. The MR is reported to change its sign when the resistance reaches R_c regardless of temperature and materials. Because of their strong spin–orbit interactions the dominant DL effect in the weakly localized regime always gives rise to a PMR while the quantum interference in the strongly localized regime causes an NMR, which naturally leads to a sign change in MR at R_c. In this paper we report MR observations in films of amorphous indium oxide at the WSLC region. The dominant effects in MR through the WSLC is investigated. As a possible way to express the observed MR near the WSLC we try to fit the data to a theoretically appropriate formula.

2. Experiments

The indium oxide samples were prepared by rf sputtering targets of indium oxide on microscope glass substrates in a vacuum chamber, maintaining a base pressure of 1–2 $\times$ 10^{-6} Torr. During the deposition at a deposition rate of 0.5 Å s^{-1}, an oxygen partial pressure of 1.0 $\times$ 10^{-4} Torr was maintained while the substrate temperature was kept at 40 °C. A stainless-steel mask was used to obtain strip-type (2 mm wide) samples with a thickness of 150 Å. The sheet resistance of the as-deposited samples at room temperature was larger than several megaohms, which clearly indicated that they were insulators. Heat treatment at 50–60 °C in air led to a monotonic decrease in sample resistance. It was necessary to carry out such a heat treatment for 1–2 days to obtain a sample resistance of several kiloohms. The detailed procedure for obtaining the samples can be found elsewhere [10, 11]. In the prepared material, indium atoms with different valences are spatially deposited and may exhibit varying degrees of short-range order on a microscopic scale. This gives rise to a change in the carrier mobility and, thus, to a change in the resistivity (or sheet resistance in two-dimensional case), which is generally accepted as a parameter of sample disorder.

Scanning electron micrographs, as well as x-ray diffraction patterns, showed that the samples obtained as described above were amorphous [11]. The resistance was measured in the temperature range 0.3–70 K by using an He(3) cryostat. A superconducting magnet was used to produce magnetic fields up to 9 T. A four-probe dc technique, using a Keithley 220 current source and a Keithley 181 nanovoltmeter, was employed. A capacitance sensor and a carbon thermometer were used to control and to read temperature, respectively.

3. Results and discussion

A series of samples was taken from a batch. Each sample has its own sheet resistance $R_\square$ (or resistivity) at room temperature as a result of different heat treatment. Figure 1 shows resistances of three samples as a function of temperature (T) in a semi-logarithmic scale. Resistances of two samples (A and B) increase rapidly as temperature decreases, which is a

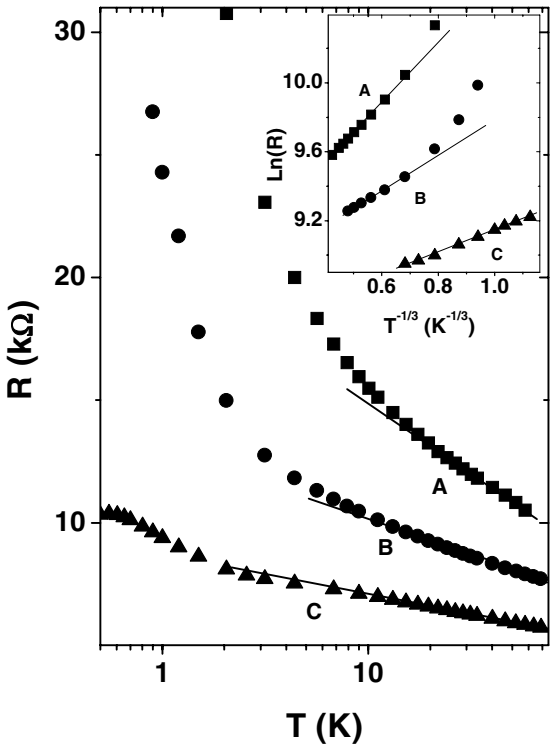

Figure 1. R versus T in semi-log scale. All the straight lines are guides for the eyes. Because of a global superconductivity the resistance obtained at $H = 8$ T is used for sample C. Inset: $\ln R$ versus $T^{-1/3}$ for the samples. Straight lines signify VRH conduction of the sample.

typical behaviour of an insulator. Sample C reveals an ambiguous behaviour between insulating and superconducting states. Samples with $R_\square$ less than that of sample C at room temperature show a superconducting transition below 1 K, which is not shown in the figure. At high T the resistance of the samples follows a $\ln T$ dependence, which indicates that these samples are effectively two dimensional in the weakly localized regime. As T decreases, however, the temperature dependence of the resistance becomes exponential. Detailed investigations show the conduction mechanism in this region is the VRH, in which the resistance varies as $R \sim \exp(T_0/T)^{1/3}$, which is followed by an Arrhenius-type activation $R \sim \exp(1/T)$ with decreasing temperature. The change in the conduction mechanism of this kind, however, is contradictory to a normal conduction process in which the VRH conduction should appear in a lower temperature range than a simple activation due to the nearest site hopping or activation to the mobility edge. Recently, it has been strongly suggested that the anomalous processes in the conduction mechanism are caused by the existence of local superconductivity in this amorphous material [12–14]. As T goes down below 1 K local superconducting granules(or droplets) are formed, even in an amorphous material, which is induced by disorder [12]. For normal hopping conduction it needs a thermal energy to break local Cooper pairs and, thus, the conduction should be activation-like. The inset of figure 1 depicts VRH behaviour of the samples at low temperatures ($T \leqslant 10$ K). For samples A and B, deviation from VRH conduction is apparent at lower temperatures, where an Arrhenius dependence becomes more appropriate. The WSLC temperature range below and above which strong and weak localization is valid (T_L and T_H, respectively) is listed in table 1. Other sample characteristics including $R_\square$ and the localization length $\xi \sim [N(0)k_\mathrm{B}T_0 d]^{-1/2}$, where $N(0)$ is the density of states at the Fermi energy, are also listed. $N(0)$ can be obtained by estimating electron concentration n through the Hall measurement and using the free electron formula $N(0) \sim (3m/\hbar^2)(3\pi^2)^{-2/3}n^{1/3}$.

Table 1. Characteristics of the samples.

Sample	$R_{\square}$(300 K) (kΩ)	$R_{\square}$(4.2 K) (kΩ)	T_0 (K)	ξ (Å)	WSLC range T_L–T_H (K)
A	7.89	20.1	4.91	433	10–30
B	6.40	12.1	1.20	876	8–20
C	4.84	7.47	0.92 ($H = 8$ T)	1000 ($H = 8$ T)	3–10

We have already reported [14] the details of the MR at low temperatures for samples lying near the superconductor–insulator transition (samples A and B). In the case of an inhomogeneous superconductor such as a granular one superconducting granules with insulating matrix surrounding them exist at a low enough temperature. Even in a deep insulating side localized superconducting granules (or, a certain size of localized clusters composed of them) can exist, which limits the hopping conduction due to the reduced single-electron density of states [15]. Such a local superconductivity is destroyed in the presence of a magnetic field by two steps. Weak links between superconducting granules break down first in low magnetic fields while localized electron pairs separate into individual electrons in relatively high magnetic fields. As a consequence a material shows initially a PMR due to the junction (link) breaking at low fields, followed by an NMR due to the pair breaking at higher fields.

In addition to an anomalous processes in the conduction mechanism, the existence of local superconductivity is also reflected in the MR. Such MRs ($\ln[R(H)/R(0)]$) of our samples are depicted in figure 2. The PMR and NMR are evident at low temperatures ($T \leqslant 1$ K). Furthermore, both the PMR and the NMR tend to decrease and become small with increasing temperature, and finally another PMR, which is totally different from the first one, appears to be significant. This second PMR extends over a wider field range and tends to saturate at 4–5 T of magnetic field, which is a typical behaviour of the spin-dependent intrastate interaction effect [8]. Different from the case of samples A and B, the MR of sample C does not become negative at low temperatures where local superconductivity prevails. Since the sample C is much less resistive it probably has more coupled links between superconducting granules than other samples. It may rather be composed of localized superconducting clusters than localized small granules, as one can imagine from the R–T behaviour of the sample. In other words PMR due to junction breaking is larger than NMR caused by pair breaking in this sample. Nevertheless, the appearance of the second PMR is similar to that of other samples.

MR variation near the WSLC region is depicted in figure 3. First of all, no abrupt change in MR is observed passing through the WSLC. For sample A, NMR appears all through the field and temperature range (10–30 K). PMR (except the high-field region) changes to purely NMR in the case of other samples in the WSLC region (8–20 K for sample B and 3–10 K for sample C) as temperature increases. Such a sign change in the MR is interesting in the sense that effects on MR developed in one regime should be different from those derived in the other regime. Thus the dominant effect should change through the WSLC. The only dominant effect on the MR below the WSLC temperature but above 1 K is the intrastate interaction (IS), which decreases as temperature increases and approaches WSLC. Above the WSLC one can presume the dominant part of the MR originates from the DL term. Since the DL effect makes an NMR one can expect the change from PMR to NMR through the WSLC. Roughly speaking, such a change in the MR seems to take place in our samples since their WSLC region coincides partly (very marginally for sample A) with temperature ranges where the change from PMR to NMR is expected. Considering the matter from a different point of view, however, one can

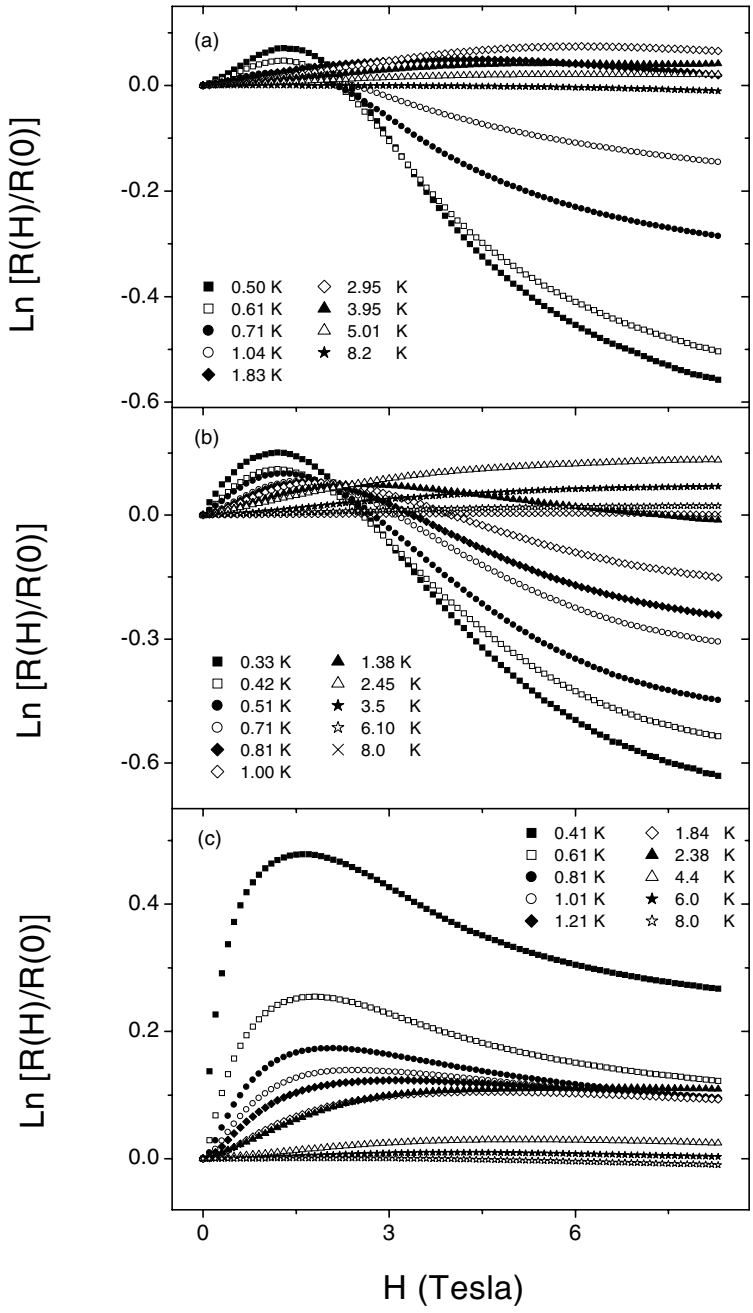

Figure 2. MR of the samples in the low-temperature region.

observe that the change from PMR to NMR takes place commonly at 8–10 K regardless of the WSLC range of the samples.

To investigate MR behaviour in more detail we tried to fit our MR data near the WSLC to a fitting formula which includes the DL term as well as the IS effect, and is given by

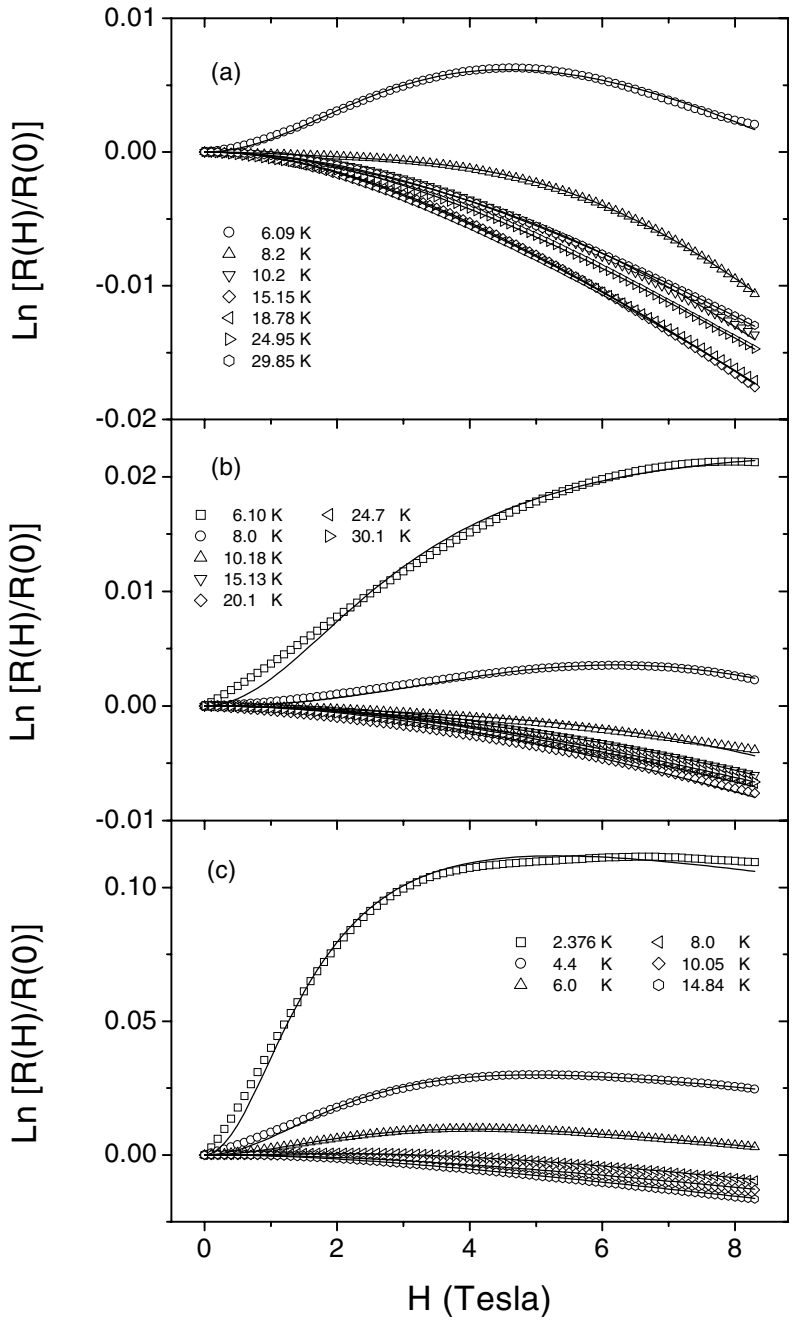

Figure 3. MR of the samples in the WSLC region. Solid curves are the fits by equation (1) in the text.

$$\ln\left[\frac{R(H)}{R(0)}\right] = -R(0)\left(\frac{e^2}{2\pi^2\hbar}\right) f_2(x) + \frac{A_{\mathrm{IS}}H^2}{H^2 + H_{\mathrm{IS}}^2}. \tag{1}$$

The first term on the right-hand side of the above equation represents the DL contribution where $f_2(x) = \ln(x) + \Psi(1/2 + 1/x)$. Here $\Psi(x)$ is a digamma function in which

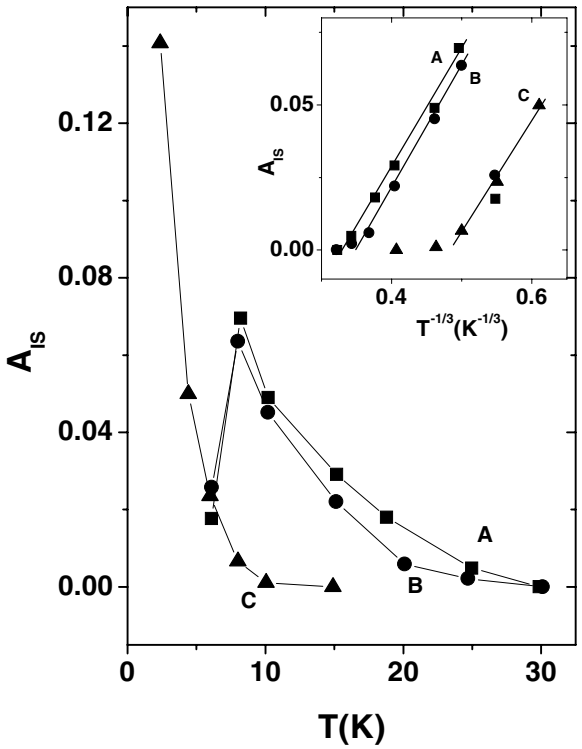

Figure 4. A_{IS} as a function of temperature. Inset: A_{IS} versus $T^{-1/3}$ for the samples. The straight lines are guides for the eyes.

$x = 4L_{in}^2 eH/\hbar$ with L_{in} the inelastic scattering length. We neglect the spin–orbit coupling in our samples and assume there are no magnetic impurities. The second term denotes the IS effect. Since the original expression of Kurobe and Kamimura [8] for the IS effect is too complicated for actual use without detailed information such as localization lengths (inner and outer) and the density of states, we use a phenomenological formula proposed by Frydman and Ovadyahu [16]. H_{IS} is a characteristic field for spin alignment and is given by $H_{IS} = a_1(k_B T_0^{1/3}/\mu_B)T^{2/3}$, where a_1 is a constant of the order of unity and μ_B the Bohr magneton. A_{IS} is the saturation value of the MR and has a temperature dependence $A_{IS} = a_2(T_0/T^{1/3})$, where a_2 is another constant. The fitting results are represented by the solid curves in figure 3. To justify our fitting we tried to examine the temperature dependence of fitting parameters. The best-fit results of A_{IS} for the samples are depicted in figure 4. First of all, the values of A_{IS} for samples A and B drop sharply as the temperature decreases below 8 K. There is no particular reason for the drop and we believe this reflects the limit of the fitting formula since it (equation (1)) is presumed valid within the WSLC range (T_L–T_H) only. Actually we found that the fitting itself becomes bad at temperatures lower than T_L, especially in the low-field region (in the case of sample B, for instance, the least chi-square value observed at 6 K rises almost 20 times as much as that observed at 10 K). At a temperature higher than T_H such a fitting inferiority is not significant because of the small MR. The most remarkable observation is that A_{IS} decreases with temperature and vanishes as the high limit of the WSLC region (T_H) is approached from the low-temperature side for each sample (around 10, 20 and 25–30 K for samples C, B and A, respectively). This implies the IS effect exists in the WSLC region up to T_H, above which the weak localization is valid and, thus, the IS effect cannot be justified. The inset of figure 4 shows the $T^{-1/3}$ dependence of A_{IS} in the WSLC region. Also

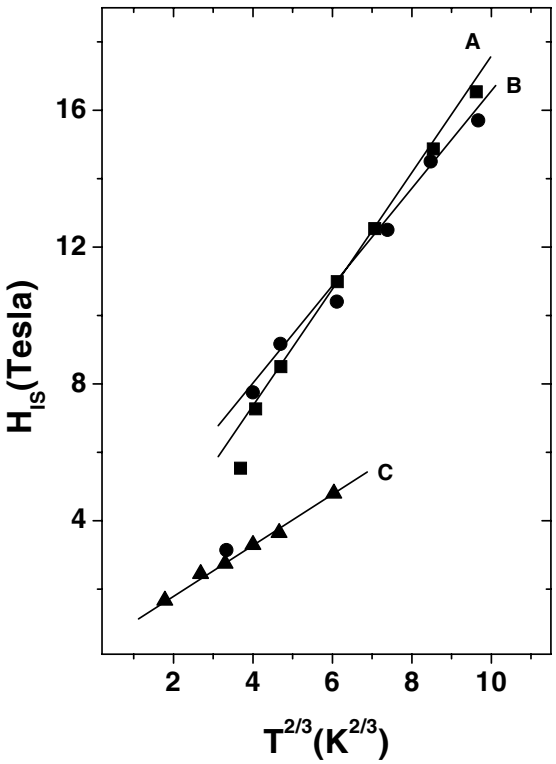

Figure 5. H_{IS} versus $T^{2/3}$ for the samples. The straight lines are guides for the eyes.

an appropriate temperature dependence of H_{IS}, a certain saturation field of the IS effect, is shown in figure 5. The agreements with each theoretical expectation are quite good.

L_{in} usually decreases with increasing temperature due to various thermal agitations. L_{in} of samples A and B, however, shows a sharp decrease below 8 K (figure 6). In this case the strong localization is valid below 8–10 K, where L_{in} cannot be justified for the samples. Thus, as in the case of A_{IS}, this indicates the limit of our fitting formula. For sample C, however, L_{in} seems to follow a correct temperature dependence down to 2–3 K, the low limit of WSLC (T_{L}) of this sample. Since $L_{\mathrm{in}} = \sqrt{D\tau_{in}}$ and $\tau_{in} \sim T^{-p}$, where D and τ_{in} are the diffusion constant and inelastic scattering time, respectively, $L_{\mathrm{in}} \sim T^{-p/2}$. The best fit seems to be obtained with $p = 1$ for the samples (inset of figure 6), which is consistent with theoretical prediction when the electron–electron inelastic scattering is dominant [17, 18]. The same value of p has already been observed experimentally in two-dimensional films of indium oxide [19, 20].

It is worth noting that the IS effect may become insignificant at a temperature lower than T_{H}, which is the observed high-temperature limit of the effect. The intrastate interaction serves an important role when a localized electron hopping occurs between two singly occupied states or between doubly occupied and empty states [8]. In these hopping processes an intrastate interaction energy U is provided or absorbed by the surroundings. A strong enough magnetic field makes the spin of localized electrons align, which reduces the hopping rate between those described states and, thus, gives rise to a PMR. This PMR is expected to decrease with increasing temperature. At a high enough temperature where $k_{\mathrm{B}}T \gg U$, the intrastate interaction becomes veiled by thermal motions. Thus PMR due to the effect may be markedly diminished at temperatures above $T_{\mathrm{s}} = U/k_{\mathrm{B}}$. Although we do not know the exact magnitude

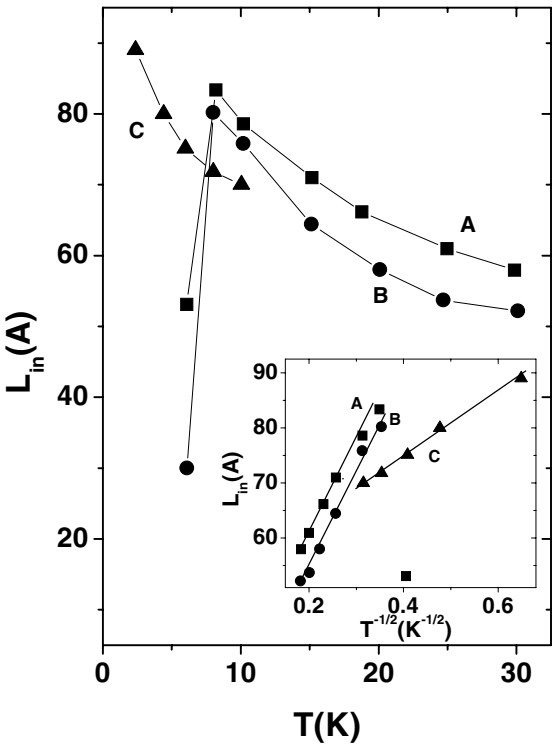

Figure 6. $L_{\rm in}$ as a function of temperature. Inset: $L_{\rm in}$ versus $T^{-1/2}$ for the samples. The straight lines are guides for the eyes.

of U, a rough estimation of $T_{\rm s}$ can be obtained by assuming $U \sim e^2/\chi\xi$, where χ is the static dielectric constant. With $\chi \sim 10$, a typical value for a metal oxide, we obtain $T_{\rm s}$ of 38, 20 and 17 K, for samples A, B and C, respectively. These values of $T_{\rm s}$ are slightly higher than (or equal to, in the case of sample B) $T_{\rm H}$ in our samples. In the case of ($T_{\rm H} > T_{\rm s}$), however, theoretical consideration enables us to expect that the IS effect may be cut off near $T_{\rm s}$ with increasing temperature before $T_{\rm H}$ is reached.

It should be mentioned that our fitting formula (equation (1)) is self-consistent in the sense that each term limits its validity within WSLC region only, which is assumed from the beginning. The low-temperature limit of validity in $A_{\rm IS}$ and in $L_{\rm in}$, vanishing of $A_{\rm IS}$ as $T_{\rm H}$ is approached, for instance, are not intentionally obtained. The MR data fitting just results in such a way that they are self-consistent. According to the fitting results, both the DL and the IS effects exist within WSLC region. The relative magnitude, however, depends on the sample. For sample C, IS $\geqslant$ DL through the WSLC region while IS $\leqslant$ DL is maintained for the other samples. In any case, however, IS $\sim$ DL is obtained commonly at 8–10 K, of which the origin is not clear at the moment, but our fitting formula may give a clue to form a rough idea. The MR sign change occurs when the value of equation (1) becomes zero. For a weak enough field ($H/T \ll 1$) we find $T \sim A(R^3(0)/T_0)$ at the temperature where the sign change in the MR occurs ($T_{\rm cr}$). Here, A is a constant which is sample independent. If $R^3(0)/T_0$ is sample independent, $T_{\rm cr}$ will be sample independent. Although it is difficult to obtain the sample dependence (or T-dependence) of $R(0)$ in the WSLC region a simple substitution of observed values for $R(0)$ and T_0 enables us to estimate the sample independence of $T_{\rm cr}$. At around 9 K, we obtain $R^3(0)/T_0$ values of 9.5, 10.3 and 10.6 ($\times 10^{11}$) for samples A, B and C, respectively. Thus one can see that $T_{\rm cr}$ does not vary much from one sample to another. In other words, two competing terms in MR become equal in absolute magnitude at a certain

temperature, which is almost independent of the sample measured.

To investigate more substantial change in MR through the WSLC a sample with lower WSLC temperature range may be desired. These samples were, however, not easily obtained. First of all, any sample which is less resistive than sample C tends to show global superconductivity. Second, these samples do not show WSLC. In other words, they lie in the weakly localized regime down close to the superconducting transition, even in the presence of a high magnetic field. Thus the WSLC range of sample C lies almost at the low limit in this material. On the other hand, samples with WSLC temperature range higher than that of sample A are not difficult to obtain. The MR of these samples, however, is too small to measure at high temperatures. Furthermore, it is not recommended to turn up a superconducting magnet to such a high temperature in our cryostat system.

4. Conclusions

The MR of amorphous indium oxide films in the WSLC region was measured. The change from PMR to NMR was observed commonly for all three measured samples as temperature increases and passes through 8–10 K, which falls within the WSLC range (very marginal for a sample) of each sample. The observed MR was fitted to a formula consisting of theoretical expressions for the intrastate interaction term and the DL term. Within the WSLC region, temperature dependences of the fitting parameters are in accord with theoretical expectations. The intrastate interaction term persists up to the high limit of the WSLC region, above which the weak localization is valid, while the DL effect is evident down to the low limit of the WSLC region, below which the strong localization prevails. The sum of the two terms results in the sign change in MR at 8–10 K regardless of the WSLC region of the samples. Finally, the temperature dependence of $L_{\rm in}$ implies that $p = 1$ where $\tau_{in} \sim T^{-p}$, which is consistent with theoretical predictions when the electron–electron inelastic scattering is dominant.

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