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Electron weak localization and electron–electron interaction effects on magneto-conductivity in In–Ga–Zn oxide films

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ABSTRACT

We investigated the magnetoconductivity $\Delta\sigma(H,T)$ defined by a function of magnetic field H and temperature T for three-dimensional indium–gallium–zinc oxide films in the resistivity ρ range of $0.076 \times 10^{-3}\ \Omega$ m $\leq \rho(2.0\ \mathrm{K}) \leq 0.55 \times 10^{-3}\ \Omega$ m. Here, $\Delta\sigma(H,T)$ is the $\Delta\sigma(H,T) \equiv 1\ /\ \rho(H,T) - 1\ /\ \rho(0,T)$. With increasing ρ, the contribution $\Delta\sigma_{\mathrm{EEI}}$ due to the electron–electron interaction (EEI) effect overcomes the contribution $\Delta\sigma_{\mathrm{WL}}$ due to the weak localization (WL) effect. The sign of $\Delta\sigma(H) = \Delta\sigma_{\mathrm{EEI}} + \Delta_{\mathrm{WL}}$ changes from positive to negative with increasing magnetic field, particularly at low temperatures. To perform a systematic investigation of $\Delta\sigma_{\mathrm{EEI}}$, we obtained the contribution of $\Delta\sigma_{\mathrm{EEI}}$ using the relation $\Delta\sigma_{\mathrm{EEI}}(H,T) = \Delta\sigma^{\mathrm{exp.}}(H,T) - \Delta\sigma_{\mathrm{WL}}^{\mathrm{theo.}}(H,T)$, where $\Delta\sigma_{\mathrm{WL}}^{\mathrm{theo.}}(H,T)$ is estimated by fitting the WL theory to data at low magnetic fields. It was found that i) $\Delta\sigma_{\mathrm{EEI}}(H,T)/\sqrt{T}$ as a function of H/T for each film collapses onto a single universal curve at a magnetic field of up to 5 T and in the temperature range between 2.0 and 50 K. ii) From the analyses of $\Delta\sigma_{\mathrm{EEI}}(H,T)/\sqrt{T}$ in the high and low H/T regions with the EEI theory, the screening factors $F_{\Delta\sigma,H}$ and $F_{\Delta\sigma,L}$ were estimated, respectively. iii) The $F_{\Delta\sigma,H}$ values satisfy the theoretical prediction as $0 < F < 1$. iv) With increasing ρ, the magnitudes of both $F_{\Delta\sigma,H}$ and $F_{\Delta\sigma,L}$ essentially decrease to approach 0 at $\rho_c \approx 1.3 \times 10^{-3}\ \Omega$ m, where the metal–insulator transition is suggested to occur.

1. Introduction

Many investigations of transparent conducting indium oxides doped with metals have been carried out focusing on the electrical and optical properties from a practical viewpoint [1,2]. Recently, owing to the demand for flexible electronics and devices, there has been much interest in amorphous indium–gallium–zinc oxide (IGZO) systems [3,4]. In addition to practical studies to achieve higher quality, fundamental investigations of the electrical properties of indium oxides are very interesting from the viewpoint of the investigation of quantum corrections in dirty systems [5,6]. Owing to the weak localization (WL) and electron–electron interaction (EEI) effects, the conductivity σ changes as $\sigma(T) = \sigma_0 + \sigma'_{\mathrm{EEI}}(T) + \sigma'_{\mathrm{WL}}(T)$ at sufficiently low temperatures. The first term is due to the classical residual conductivity, and the second and third terms are due to the contributions of WL and EEI effects, respectively. The magneto-conductivity $\Delta\sigma(H,T) \equiv 1\ /\ \rho(H,T) - 1\ /\ \rho(0,T)$, where ρ, H and T are the resistivity, the strength of magnetic field and the temperature respectively, has also been analyzed at the relatively low magnetic fields with the WL theory [7,8] mainly to derive the temperature dependence of inelastic scattering time τ_{in} given by $\tau_{in} \propto T^{-p}$ [9–12]. Regarding the sign of the magneto-conductivity $\Delta\sigma_{\mathrm{WL}}$ due to the WL effect in the frame of the WL theory [7], $\Delta\sigma_{\mathrm{WL}}$ takes negative or positive values depending on the magnitude of the ratio $\tau_{\mathrm{so}}/\tau_{\mathrm{in}}(T)$, where τ_{so} is the temperature independent on spin–orbit scattering time. The conditions $\tau_{\mathrm{so}}/\tau_{\mathrm{in}}(T) \gg 1$ and $\tau_{\mathrm{so}}/\tau_{\mathrm{in}}(T) \ll 1$ give $\Delta\sigma_{\mathrm{WL}}(H,T) > 0$ and $\Delta\sigma_{\mathrm{WL}}(H,T) < 0$, respectively. The latter is called an anti-WL. As suggested by Abrikosov and Gorkov, τ_{so} depends on the atomic number Z as $\tau_{\mathrm{so}} \propto 1\ /\ Z^4$ [13]. This means that the sign of $\Delta\sigma_{\mathrm{WL}}$ essentially depends on the material, that is, $\Delta\sigma_{\mathrm{WL}} > 0$ for light metals such as Mg [14] and $\Delta\sigma_{\mathrm{WL}} < 0$ for heavy metals such as Au [15]. It is proposed that the sign of $\Delta\sigma_{\mathrm{WL}}$ for oxide-degenerated semiconducting materials is positive, because conduction electrons come from oxygen vacancies as light atoms [16].

On the other hand, the contribution of the magneto-conductivity $\Delta\sigma_{\mathrm{EEI}}$ due to the EEI effect becomes larger at high magnetic fields with decreasing temperature. Then, to understand the behavior of $\Delta\sigma(H,T)$ in a high magnetic field, it is necessary to analyze $\Delta\sigma(H,T)$ in the form of $\Delta\sigma(H,T) = \Delta\sigma_{\mathrm{WL}} + \Delta\sigma_{\mathrm{EEI}}$. The origin of the EEI effect is the retardation of the interaction between electrons in disordered systems. Electrons in such systems cannot immediately redistribute to compensate

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Table 1
Characteristics of indium–gallium–zinc oxide films. The diffusion constant D is obtained with the relation $D = (3\pi^2)^{2/3}(\hbar^2 / 3e^2)(1/m_* \rho n^{1/3})$, where we used $m_* \cong 0.55\ m_0$.

	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9
ρ (2 K) × 10^{-3}[Ω m]	0.076	0.116	0.128	0.137	0.223	0.23	0.445	0.525	0.55
n (2 K) × 10^{26}[m^{-3}]	0.72	0.5	0.48	0.5	0.22	0.24	0.16	0.13	0.11
D (2 K) × 10^{-4}[$m^2\ s^{-1}$]	0.87	0.65	0.59	0.55	0.44	0.42	0.25	0.23	0.22
τ_{so}/τ_{in}(15 K)	243	200	76.1	93.3	91.7	57.1	70.2	26.7	31.5

for the sudden change in the charge distribution. Then, the quantum correction due to the EEI effect depends on the screening factor F, which is a parameter that describes the degree of electron screening introduced by Al'tshuler et al. [17] The sign of $\Delta\sigma_{EEI}$ is always negative independent of magnetic field and temperature, and the magnetic field dependence of $\Delta\sigma_{EEI}$in a 3D system is the same as that of the anti-WL effect, i.e., $\Delta\sigma \propto -H^2$ and $\Delta\sigma \propto -\sqrt{H}$ at low and high magnetic fields, respectively [18]. For single-wall carbon nanotubes, $\Delta\sigma(H)$ was observed to take its maximum with increasing magnetic field owing to the contributions of both the WL and EEI effects [19]. However, until now, there has been little systematic investigation of F by analysis of $\Delta\sigma(H,T)$. The EEI theory [18,20] shows that $\Delta\sigma_{EEI}(T,H)/\sqrt{T}$ collapses onto a single universal function $f(H/T)$ as

$$\Delta\sigma_{EEI}(T,H)/\sqrt{T} = K(F,D)f(H/T), \quad (1)$$

where the coefficient $K(F,D)$ is a constant depending on the strength of F and the diffusion constant D. In extremely high H/T and low H/T regions, the H/T dependence of $\Delta\sigma(T,H)/\sqrt{T}$ is given by $\Delta\sigma(T,H)/\sqrt{T} = -K_H(F,D)\sqrt{H/T}$ and $\Delta\sigma(T,H)/\sqrt{T} = -K_L(F,D)(H/T)^2$, respectively, where the coefficients $K_H(F,D)$ and $K_L(F,D)$ are positive. We can estimate the magnitude of F in the EEI effect from the $K_H(F,D)$ and $K_L(F,D)$ values for both the extreme regions of H/T. As mentioned above, the present IGZO films have a characteristic of $\Delta\sigma_{WL} > 0$. However, $\Delta\sigma_{EEI}$ shows the opposite characteristic of $\Delta\sigma_{EEI} < 0$ and has a small contribution at low magnetic fields. These characteristics enable the easy separation of $\Delta\sigma_{EEI}$ from the experimental data $\Delta\sigma^{exp.}$. Therefore, the present specimen is a good candidate for the investigation of the contribution of the EEI effect to $\Delta\sigma$.

In this paper, we report detailed analyses of $\Delta\sigma$ for three-dimensional (3D) IZGO films in a metallic region. Through the investigation of $\Delta\sigma$ in wide magnetic field and temperature regions, the main purposes of this paper are to divide $\Delta\sigma^{exp.}$ into $\Delta\sigma_{WL}$ and $\Delta\sigma_{EEI}$, in order to clarify the scaling behavior of $\Delta\sigma_{EEI}$ and to investigate the dirtiness dependence of F in order to discuss the critical resistivity of the metal–insulator (M–I) transition.

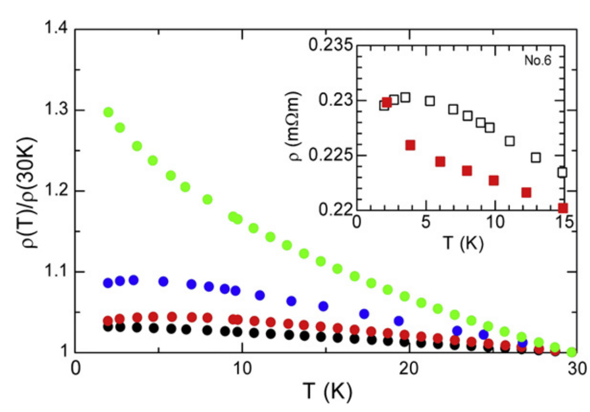

Fig. 1. $\rho(T)/\rho(30\ K)$ values for IGZO films No. 1, No. 3, No. 6 and No. 9 from bottom to top. The inset shows the $\rho(T)$ values at low temperatures for film No. 6. at $H = 0$ (□) and $H = 5$ T (■).

2. Sample preparation and experimental procedures

An IGZO ceramic target was prepared by sintering the mixture powder of In2O3, Ga2O3, and ZnO. IGZO films with a thickness $d = 350$ nm were first prepared by deposition on glass substrates by the DC-magnetron sputtering method. The base pressure was $(5.0–8.0) \times 10^{-4}$ Pa. During the deposition, the gas pressure of pure argon was essentially kept at 0.3 Pa. We obtained films in the range of 92 μΩ m ≤ ρ(300 K) ≤ 240 μΩ m, using the sensitive dependence of the O_2 partial pressure on the substrate position in the sputtering procedure. To obtain the cleanest films, as-deposited films were annealed in air for 1 h on a hot plate preheated to certain annealing temperatures below ≈550 K.

We measured the resistance R (T, H) using a standard dc four-probe technique. We applied a magnetic field of up to $H = 5$ T perpendicular to the film surface. To estimate the carrier density n, data of the Hall coefficient R_H were obtained in a standard manner. To eliminate the effect due to Hall probe misalignment, measurements were performed in both positive and negative magnetic configurations. The results were averaged over the two perpendicular field orientations. For the Hall resistance, we confirmed that a linear characteristic holds up to $H = \pm 3$ T.

In Table 1, some characteristics of the films in the present work, including ρ, n, D and the ratio τ_{so}/τ_{in}(15 K), are listed. Films No. 1 and No. 2 were prepared by annealing procedures and films Nos. 3–9 are as-deposited films.

3. Experimental results and discussion

Fig. 1 shows the temperature dependences of ρ normalized at 30 K for films No. 1, No. 3, No. 6 and No. 9. Although ρ increases with decreasing temperature, $|d\rho/dT|$ is small compared with those of typical insulating materials [21]. Even for film No. 9 with the largest ρ, $\rho(2.0\ K)/\rho(30\ K)$ is ≈1.3. Furthermore, $\rho(T)/\rho(30\ K)$ of films No. 1–No. 8 shows their maximum at a temperature T_m. For instance, the inset shows the detailed $\rho(T)$ of film No. 6 at approximately T_m when $H = 0$ and $H = 5$ T. The $\rho(T)$ at $H = 0$ clearly shows a broad peak and the magnetoresistivity $\Delta\rho = \rho(H) - \rho(0)$ essentially takes a negative value in a wide temperature range.

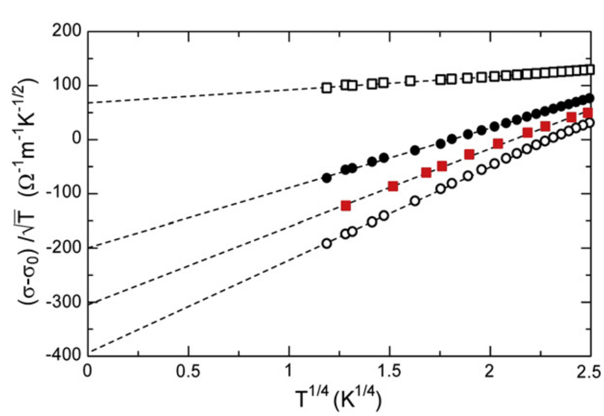

Fig. 2. $[\sigma(T) - \sigma_0] / T^{1/2}$ vs. $T^{1/4}$ for films No. 1 (●), No. 3 (○), No. 6 (■) and No. 9 (□).