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Electron weak localization, and electron–phonon interaction in amorphous zinc-doped indium oxide films

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Abstract

We have systematically investigated the temperature dependence of resistivity ρ and Hall coefficient R_H of indium zinc oxide films with thickness $d=350$ nm in the temperature range 2.0 K to 300 K. Specimen films with $\rho\simeq 3-17$ μΩ m (300 K) show metallic characteristics ($\rho\propto T$) at temperatures above 100 K. At low temperatures below 20 K, the resistivity slightly increases with decreasing temperature because of the quantum effects in disordered systems. By eliminating carefully quantum effects ρ_{quanta} and the residual resistivity ρ_0, we have found that the resistivity changes in the form of $\rho\propto\rho_0 T^2$ at temperatures below $\simeq 100$ K. This characteristic indicates the existence of resistivity $\rho_{\mathrm{el-ph-imp}}$ due to the interference effect between the impurity scattering and the electron–phonon scattering. It has been found that the temperature dependence of $\rho(T)$for all present films agrees well with the sum of the Bloch–Grüneisen term $\rho_{\mathrm{el-ph}}=\beta F(T,\Theta_D)$ and the interference term $\rho_{\mathrm{el-ph-imp}}=B_{\mathrm{el-ph-imp}}G(T,\Theta_D)$ in a temperature region 20 K to 300 K. From analyses, regarding the coefficients β, $B_{\mathrm{el-ph-imp}}$, and the Debye temperature Θ_D as fitting parameters, we obtain the $\Theta_D\simeq 970-1060$ K and the longitudinal sound velocity $v_\ell\simeq 14{,}000$ m/s under some assumptions.

Keywords: Electrical resistivity; Electron–electron interaction; Electron–phonon interaction; Interference effect

Materials exhibiting high visible transparency and relatively high electrical conductance have been extensively investigated. Recently, there is a great deal of interest in amorphous indium zinc oxide films [1,2]. Although some characteristics such as electrical resistivity [3], thermal property [4] and morphology [2] have been studied, detailed studies of the transport properties at low temperatures are few. In addition to practical studies on achieving higher quality, investigations of the fundamental characteristics of the electrical properties of amorphous indium zinc oxide films are very interesting from the viewpoint of the electrical transport in dirty systems.

It has been generally assumed that the temperature dependence of the resistivity ρ is given by the sum of two contributions, namely, the residual resistivity ρ_0 independent of temperature from random potentials and the resistivity depending on temperature from electron–phonon (el–ph) scattering. The latter term is known by Grüneisen–Bloch (G–B) formula [5]. At temperatures $T\ll\Theta_D$ (Debye temperature), the resistivity proportional to T^2 has been observed by experiments on some metallic specimens [6–9], although the G–B term gives $\rho(T)\propto T^5$ in a pure metal. As the reason for such a deviation in impure conductors, the interference mechanism, so called electron–phonon–impurity interference, has been proposed. According to the theory of Reizer and Sergeev [10], $\rho(T)$ is given by $\rho(T)=B\rho_0T^2$, where coefficient B is a constant. Until now, thin films have been mainly analyzed by the theory of the interference effect except for a few articles for thick films.

In this paper, we report the characteristics of $R(T,H)$, magnetoconductivity $\Delta\sigma(T,H)$, and Hall coefficient $R_H(T)$ in a wide temperature region for thick indium zinc oxide films. We have analyzed the $\rho(T)$ by the sum of three terms of the G–B, the quantum effect and the interference in the temperature range 20 K to 300 K.

Indium zinc oxide films were deposited on glass substrates by the DC-magnetron sputtering method using an In_2O_3–ZnO target (89.3 wt.% In_2O_3 and 10.7 wt.% ZnO, Idemitsu Kosan Co., Ltd). We prepared films with thickness $d=350$ nm, $\rho\simeq 3-17$ μΩ m

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(300 K) and carrier density $n \simeq 0.6–5\times10^{26}/\mathrm{m}^3$ by changing the gas pressure of oxygen during DC-magnetron sputtering. Fig. 1(a) shows XRD pattern of as-deposited films. The spectrum shows a broad peak at $2\theta \approx 32°$ which is the characteristic of amorphous indium zinc oxide films and another broad peak due to underlying glass substrate. For further information, Fig. 1(b) shows the XRD spectrum of post-annealed films at ≈550° for 2 h. The data show crystalline peaks instead of the broad peak. The difference of transport characteristics between amorphous and polycrystalline films will be shown in elsewhere. We have prepared the specimen films by the photoresist lift-off method in order to obtain an adequate pattern for Hall voltage measurement. We measured the resistance $R(T,H)$ using a standard dc four-probe technique. We applied magnetic field perpendicular to the film surface up to ±5 T. Data on the Hall coefficient R_{H} were obtained in a standard manner. In order 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 above $H=\pm5$ T.

For the quantum correction of weak localization (WL) and electron–electron interaction (EEI) in disordered systems, the specimen film can be treated as a three dimensional (3D) system, when the thickness d is lager than the characteristic lengths $\sqrt{D\tau\mathrm{in}}$ and $\sqrt{\hbar D/k_{\mathrm{B}}T}$, where τ_{in} and D are the electron inelastic scattering time and diffusion constant, respectively. The excess conductivity $\sigma_3' = \sigma(T) - \sigma(0)$ for 3D systems is given by the sum of WL and EEI as [11]

$$\sigma_3' = \sigma_{3,L}' + \sigma_{3,I}' = \frac{e^2}{2\pi^2\hbar} \tag{1}$$

$$\left[\sqrt{\frac{1}{D\tau_{\mathrm{in}}}} + \left(\frac{8}{3} - 4\frac{1+F/2}{1+\sqrt{1+F/2}}\right)\sqrt{\frac{k_{\mathrm{B}}T}{\hbar D}}\right]$$

in $H=0$, and as

$$\sigma_{3,I}' = \frac{e^2}{2\pi^2\hbar}\left[\frac{4}{3}\left(1 - \frac{1+F/2}{1+\sqrt{1+F/2}}\right)\sqrt{\frac{k_{\mathrm{B}}T}{\hbar D}}\right] \tag{2}$$

in magnetic fields much higher than $\hbar c/4eD\tau_{\mathrm{in}}$ and $4\pi k_{\mathrm{B}}T/g\mu_{\mathrm{B}}$, where the quantity F in EEI is a parameter that describes the degree of electron screening introduced by Altshuler et al. [12]; $F=1$ for complete screening and $F=0$ for bare screening.

For the el–ph interaction, contributing to the temperature dependent resistivity at a whole temperature region, between electron and longitudinal phonon, G–B formula [5] is well known. According to the recent theory, the resistivity in a disordered metals is given as follows [13,14],

$$\rho_{\mathrm{el-ph}} = \beta F(\Theta_{\mathrm{d}}, T), \tag{3}$$

where $\beta = \beta_l k_{\mathrm{B}}\Theta_{\mathrm{d}}^4 m\tau\rho/2\hbar p_{\mathrm{F}}^4 u_l^4 = \beta_l k_{\mathrm{B}}\Theta_{\mathrm{d}}^4 m/2\hbar p_{\mathrm{F}}^4 u_l^4 ne^2$ and $F(\Theta_{\mathrm{d}},T)$ is given by

$$F(\Theta_{\mathrm{d}}, T) = T\left(\frac{T}{\Theta_{\mathrm{d}}}\right)^4 \int_0^{\Theta_{\mathrm{d}}/T} \frac{x^5}{(e^x-1)(1-e^{-x})}dx. \tag{4}$$

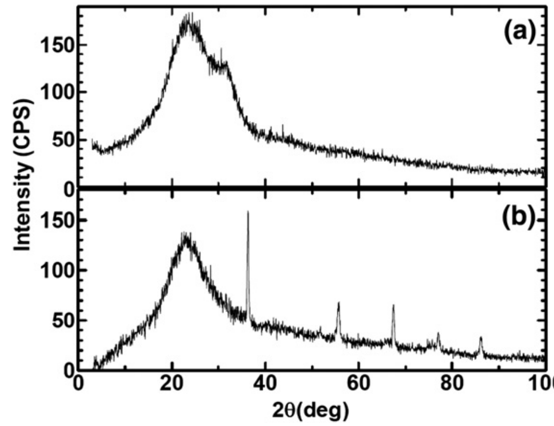

Fig. 1. (a) and (b) show XRD spectra of the indium zinc oxide film deposited at room and the film post-annealed at 550°, respectively.

The interference between electron–phonon and electron–impurity scattering gives a correction to Matthiessen rule. Interference term is given as [10]

$$\rho_{\mathrm{el-ph-imp}} = B_{\mathrm{el-ph-imp}} G(\Theta_{\mathrm{d}}, T), \tag{5}$$

where $B_{\mathrm{el-ph-imp}} = [2(u_\ell/u_{\mathrm{t}})\beta_{\mathrm{t}} + (\pi^2/16-1)\beta_\ell](2\pi^2 k_{\mathrm{B}}^2/3E_{\mathrm{F}}p_{\mathrm{F}}u_\ell)\rho_0 \equiv B\rho_0$. The function $G(\Theta_{\mathrm{d}},T)$ is given as follows,

$$G(\Theta_{\mathrm{d}}, T) = T^2\left(\frac{6}{\pi^2}\right)\int_0^{\Theta_{\mathrm{d}}/T}\left[\frac{x^2e^x}{(e^x-1)^2} - \frac{x}{e^x-1}\right]dx, \tag{6}$$

where β_{t} and β_ℓ are the coupling constants with transverse and longitudinal phonons, respectively. At low temperatures, $T<0.1\Theta_{\mathrm{d}}$, Eq. (6) is proportional to T^2 and is a constant at sufficiently high temperatures.

The resistivity for all films shows metallic temperature dependence except for sufficiently low temperatures. Generally, in imperfect specimens, it is well known that the electrical resistivity approaches a finite residual resistivity, because the electron–phonon scattering vanishes at zero temperature. However, in the dirty systems, we must consider the effect due to quantum corrections $\left(\rho_{\mathrm{quanta}} \propto -\sqrt{T}\right)$ as known from Eqs. (1) and/or (2). Therefore, we can observe $\sigma_{\mathrm{quanta}} \propto \sqrt{T}$ as a dominant contribution from these corrections at very low temperatures $T<4$ K, where the magnitude of $|d\rho_{\mathrm{el-ph}}/dT|$ is assumed to be negligible compared with that of $|d\rho_{\mathrm{quanta}}/dT|$. Fig. 2(a) shows temperature dependence of the conductivity at low temperatures for the cleanest film with the lowest value $\rho \simeq 3$ μΩ m (300 K) in the present investigation. The open and closed marks correspond to data at $H=0$ and $H=5$ T, respectively. The temperature dependence of $\sigma = A\sqrt{T}$ indicates that the dominant contribution to the resistivity comes from EEI, because the excess conductivity due to WL is theoretically given by $\sigma \propto T^{3/4}$ [15]. Taking into the magnitudes of the coefficient A for both cases of zero and strong magnetic fields, we can obtain the quantity $F \approx 0$ from Eqs. (1) and (2). In order to confirm that the transport characteristics at low temperatures are due to the quantum corrections, measurements of conductivity σ were also performed at various temperatures as a function of the external field. Fig. 2(b) shows that the magnetoconductivity defined by $\Delta\sigma = 1/\rho(H) - 1/\rho(0)$ is positive and