The temperature dependence of Hall mobility of the oxide thin film In$_2$O$_3$-ZnO

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Abstract. We report that temperature dependence of Hall mobility of the strongly disordered films In$_2$O$_3$-ZnO. We made targets by mixing ZnO into In$_2$O$_3$ at the ratio 0.5 ~ 2 wt%. Sputtering those targets on glass substrate by DC magnetron method, amorphous films with 25 nm thickness were obtained. By annealing at $T = 150 ~ 350 \degree C$ in the air, oxygen defect decreased and the conductance decreased. We obtained films with conductivity 0.2mS/m ~ 300S/m. In the temperature range $T = 90~300K$, we measured the Hall effect of these films. The density of electron was $4 \times 10^{18} ~ 1.2 \times 10^{22} m^{-3}$ at the room temperature. The Hall mobility $\mu_H$ shows the thermal-activation-like temperature dependence $\mu_H = AT^{-1/2} \exp(E_a/k_B T)$, where $E_a$ is activation energy. By fitting, we obtained $E_a = 60 ~ 86$ meV.

1. Introduction
The motion of electron in amorphous materials and magnetic field is very interesting[1,2]. The sign anomaly in Hall coefficient is reported in doped amorphous Si:H and amorphous Ge:H by E.K.Sichel et al.[3]. Okamoto et al. have studied the behavior of weak-field Hall conductivity near the mobility edge and found that the anomalous sign in the Hall coefficient can occur if the mean free path of carriers is shorter than a critical value[4]. Previous studies performed by non-sensitive voltmeter. Recently, very sensitive electrometers etc were developed. In very low mobility and very high resistance materials, the Hall effect has been able to be measured[5]. A.Takagi et al have studied the mobility of InGaZnO[6]. On the other hand, the oxide film In$_2$O$_3$-ZnO is useful for transparent conducting film of solar cells. The oxide film In$_2$O$_3$-ZnO is considerable attention[7,8]. The various resistance films can be obtained by controlling concentration of In$_2$O$_3$ and ZnO and annealing. The temperature dependence of mobility of these films with low resistivity is described by scattering mechanism[9-10]. We report that temperature dependence of Hall mobility of the strongly disordered In$_2$O$_3$-ZnO.

2. Theoretical prediction
The activation type of the temperature dependence of resistivity as follows,
The Hall coefficient is as follows,
\[ R_H = -\frac{E_y}{B z J_\sigma} = -\frac{1}{ne} \]  
(2)

The relation of the resistance and mobility as follows,
\[ \sigma = \mu en \]  
(3)

Friedman et al. calculated by random phase model as follows \[12\]
\[ \mu_H = \frac{ea^2}{\hbar} \]  
(4)

Nagel et al. considered that with decreasing T the conduction becomes hopping type and the hall effects disappears as follows\[13\]
\[ \mu_H = \mu_0 \left\{ \frac{(E_c - E_f) + W}{kT} \right\} \]  
(5)

Here \( E_c, E_f \) and W is the energy of conduction band, the Fermi energy and work function, respectively.

J.Y.W. Seto calculated the effective mobility using the grain-boundary model \[14\]
\[ \mu_H = Lq \left( \frac{1}{2\pi n^2 k_B T} \right)^{1/2} \exp \left( -\frac{E_B}{k_B T} \right) \]  
(6)

3. Sample preparation and Experimental method

We made the targets by mixing ZnO into In\(_2\)O\(_3\) at the ratio 0.5wt%~2wt%. Sputtering these targets on glass substrates by the DC magnetron method, amorphous films with 25 nm thickness were obtained. By annealing, oxygen defects decreased and the conductance decreased.

We used the van der Pauw Method to measure the resistivity and the Hall coefficient of samples\[15,16,17\]. The current of sample is induced by the Keithley220 Programmable Current Source. The voltage of sample was measured by the electrometer Keithley 6517 & 6514. The temperature of sample was obtained from the resistance of Pt100 thermometer. The samples are vacuumed at ~ 10\(^{-3}\) Pa by diffusion pomp. The samples were cooled down to 90K by liquid Nitrogen. We measured the resistivity and Hall coefficient in the range from the room temperature to liquid Nitrogen temperature cooling by liquid Nitrogen.

4. Experimental result and discussion

Figure 1 shows the Arrhenius plot of the resistivity. The temperature dependence of the resistivity is Arrhenius type. We fitted equation (1) to the data and obtained the value \( E_A \).
Figure 1. The temperature dependence of resistivity of various samples.

Figure 2. The temperature dependence of carrier density in various samples.

Figure 3. The temperature dependence of the Hall mobility. The Hall mobility shows the Arrhenius type temperature dependence.

We obtained the carrier density by using equation (2). Figure 2. shows the temperature dependence of carrier density. The temperature dependence of carrier density shows the simple activation type behaviour. We obtained the Hall mobility by the relation equation (3). Figure 3 shows the temperature dependence of Hall mobility. The scattering rate due to electron-electron scattering and electron-phonon scattering with decreasing of $T$. These scattering mechanisms are not dominant to the
temperature dependence of Hall mobility. The dotted lines are calculated from equation (4) and (5). The Nagel model (5) is not fitted to data. The all date of mobility is larger than the value calculated from Fried man model(4). We fitted equation (6) to the data and obtained $E_B = 86\text{meV}(0.5\%), 60\text{meV}(1\%), 78\text{meV}(2\%)$. We associate the Anderson localization and the hopping with the activation type of Hall mobility.

In summary, we made the polycrystalline In$_2$O$_3$-ZnO thin film. We measured the Hall effect of very low mobility and obtained the activation type of hall mobility.

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