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Mechanism of Electrical Conduction in Polycrystalline InGaAs Films

T. Okuzako*, Y. Torii , and Y. Kajikawa

Interdisciplinary Graduate School of Science and Engineering, Shimane University,
1060 Nishikawatu, Matsue 690-8504, Japan
E-mail : s099411@matsu.shimane-u.ac.jp

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Abstract. Polycrystalline $In_{1-x}Ga_xAs$ films having Ga compositions of x = 0-1 and the thickness of about 1 μm were grown on glass substrates at 240 and 350 °C by molecular-beam deposition. Hall-effect measurements at 100-390 K revealed that the electron density of the samples having Ga compositions of $x \leq 0.30$ was almost independent of the measurement temperature, while that of the samples having $x \geq 0.36$ decreased with decreasing temperature. The electron mobility of the samples having Ga compositions of $x \leq 0.21$ was almost independent of the measurement temperature, while that of the samples having $x \geq 0.30$ decreased with decreasing temperature. The temperature dependence of electron density is explained assuming the existence of three donor levels at the most. The temperature dependence of electron mobility is explained in terms of thermionic electron emission over the grain-boundary barriers.

Introduction

Polycrystalline Si-TFTs are used for driving organic electroluminescence (EL) elements. However, in order to manufacture polycrystalline Si-TFTs, it is necessary to recrystallize amorphous Si by high-temperature process at 600 °C or higher[1]. Therefore, polycrystalline Si-TFTs can be grown only on thermally resistant substrates. This leads a problem that one cannot make use of the advantage of organic EL elements which can be manufactured on plastic films.

Besides Si polycrystal, polycrystals of oxide semiconductors such as ZnO[2] are investigated as materials for TFTs. There is, however, a problem of low mobility though polycrystalline ZnO can be grown at lower temperatures than polycrystalline Si.

On the other hand, the polycrystals of III-V compound semiconductors have been scarcely investigated as materials for TFTs. In our previous study, however, polycrystalline InAs was deposited on a plastic film at 230 °C, and it showed an electron mobility higher than 400 cm^2/Vs[3]. Moreover, when we deposited InGaAs polycrystal on glass by molecular-beam deposition at 240 °C, the mobilities of the samples with low Ga compositions were almost equal to those of the polycrystalline InAs[4]. Since InGaAs has larger band-gap energies than InAs, polycrystalline InGaAs is expected as the most suitable material for flexible TFTs. However, the influence of substrate temperature on the mobility and the conduction mechanism in polycrystalline InGaAs are not clear. In this study, we clarify the influence of substrate temperature on the electrical properties, and study the mechanism of electrical conduction in the polycrystalline InGaAs.

Experiments

Polycrystalline $In_{1-x}Ga_xAs$ films with various Ga compositions (x = 0, 0.21, 0.30, 0.36, 0.44, 0.57, 0.64, 1) were deposited on non-alkali glass (Corning7059) substrates at substrate temperatures of T_g = 240 and 350 °C by molecular-beam deposition. The beam equivalent pressures of Ga and In at each deposition were adjusted so that the growth rate becomes about 1μm/h. The films of 1μm in thickness were deposited so that their Ga compositions can be measured in terms of electron probe microanalysis (EPMA). The temperature dependences of electron density and electron mobility were examined by Hall-effect measurements using the van der Pauw method in the temperature range of 100-390 K. The surface was observed by AFM, and the mean radius r of crystal grains was estimated by assuming the following expression:

$$A = N_G \pi r^2, \tag{1}$$

where A = 2μm×2μm is the scanning area of an AFM image and N_G is the number of crystal grains observed in the scanning area of A.

Experimental results

Fig.1 shows the Ga composition dependence of the mean grain radius. As can be seen in Fig.1, the mean radius at 350 °C is larger than that at 240 °C by about 20 nm at each Ga composition. The mean radius decreases slightly as the Ga composition increases.

Figs.2(a) and 2(b) respectively show the Arrhenius plots of the electron density and the electron mobility of the polycrystalline InGaAs grown at 240 °C. As can be seen in Figs.2(a) and 2(b), both the electron density and the electron mobility showed little change within the

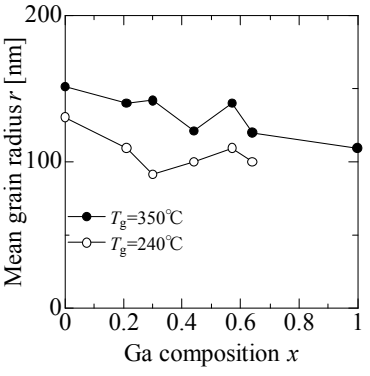

Fig.1 Ga composition dependence of the mean grain radius.

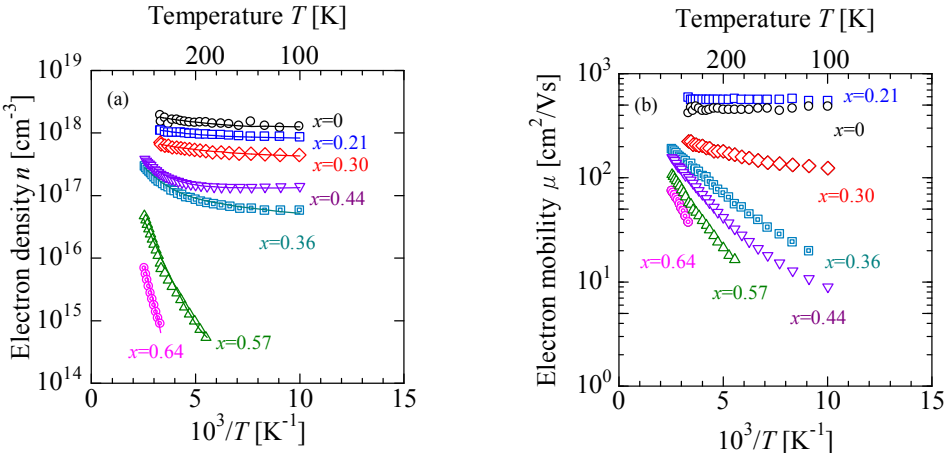

Fig.2 Temperature dependence of (a) electron density and (b) electron mobility of polycrystalline InGaAs grown at 240°C.

measurement temperature range of 300-100 K for the samples having lower Ga compositions than 0.21. On the other hand, for higher Ga compositions than 0.30, both the electron density and the electron mobility decreased with decreasing measurement temperature. Those temperature dependences were enhanced as the Ga composition increases, and were diminished with decreasing measurement temperature. The mobility of the sample having a Ga composition of 0.57 can not be measured at lower temperatures than 170 K because of its high resistivity. The similar temperature dependences of the electron density and the electronic mobility were observed also for the samples grown at 350 °C.

Discussion

Temperature dependences of the Fermi level and electron density. The temperature dependence of the Fermi level in each sample was calculated from the measurement results of the electron density using the relation of

$$n = N_C(T) F_{1/2}(\eta), \tag{2}$$

where $\eta = (E_F - E_C) / k_B T$, E_C is the energy of the conduction band minimum(CBM), $N_C(T)$ is the effective density of states of the conduction band, and the Fermi-Dirac integral $F_{1/2}(\eta)$ is defined as

$$F_{1/2}(\eta) = \frac{\sqrt{\pi}}{2} \int_0^\infty \frac{x^{1/2}}{1 + e^{(x-\eta)}} dx. \tag{3}$$

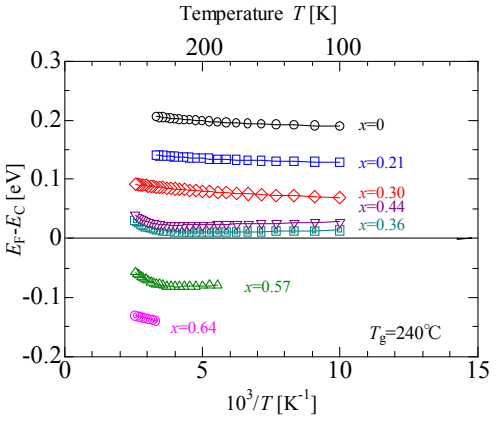

Fig.3 Temperature dependence of the Fermi level with respect to the CBM.

Fig.3 shows the temperature dependence of E_F-E_C in the samples grown at 240 °C. As can be seen in Fig.3, in the samples having lower Ga compositions than 0.44, electrons are degenerated while the spatially averaged values of E_C lie higher than E_F in the samples having higher Ga compositions than 0.57.

As can be seen in Fig.2(a), the slope of the Arrhenius plot of the electron density decreased with decreasing temperature in the samples having lower Ga compositions than 0.36. This suggests that more than two donor levels exist in these samples. When assuming three donor levels, the temperature dependence of the electron density is given by the following relation of the neutrality condition among the electric charges [5]:

$$n = \sum_{i=1}^{3} N_{Di} - \sum_{i=1}^{3} N_{Di} f_D(E_{Di}), \tag{4}$$

where N_{Di}'s are the densities of the donor levels while E_{Di}'s are the energies of the donor levels. $f_D(E)$ is defined as

$$f_D(E) = \left[1 + \frac{1}{2} \exp\left(\frac{E - E_F}{k_B T} \right) \right]^{-1}. \tag{5}$$

The values of N_{Di}'s and E_{Di}'s were obtained through fitting the measurement results of the

temperature-dependent electron density using Eq.(4). The curves in Figs. 2(a) and 3 show the fitting results using Eq.(4). The densities and ionization energies of the donor levels obtained by the fitting are shown in Table I for the samples grown at 240 °C. The negative values of the ionization energies ε_{D1} in Table I indicate that the dominant donor level lies in the conduction band.

Table I. The densities and ionization energies of donor levels in the samples grown at 240 °C.

x	N_{D1} [10^{18}cm^{-3}]	ε_{D1} [eV]	N_{D2} [10^{18}cm^{-3}]	ε_{D2} [eV]	N_{D3} [10^{18}cm^{-3}]	ε_{D3} [eV]
0	20	-0.17	0		0	
0.21	8	-0.11	0		0	
0.30	5	-0.055	0		0	
0.36	17	0.13	1.4	0.037	0.057	-0.05
0.44	20	0.12	1.0	0.021	0.14	-0.06
0.57	900	0.37	0		0.15	0.155
0.64	1400	0.52	0		0.002	0.13

Fig.4(a) shows the Ga composition dependences of densities N_{Di} of the donor levels. As can be seen in Fig.4, the density of the dominant donor level in the samples grown at 350 °C is almost independent of Ga composition, while that in the samples having Ga compositions of 0.36-0.64 grown at 240 °C was very high. Fig.4(b) shows the Ga composition dependences of energies E_{Di} of the donor levels with respect to the CBM together with E_F at room temperature. As can be seen in Fig.4(b), E_{D1} as well as E_F is lowered as the Ga composition increases.

In Fig.5, we plot the energy level E_{D1}-E_V of the dominant donor level with respect to the valence band maximum(VBM) as a function of the Ga composition, and compare it with the energy of the *EL*2 level in InGaAs estimated by Khirouni *et al*. [6]. The band gap energy $E_g = E_C$-$E_V = 0.36+0.505x+0.555x^2$ (eV) at room temperature is also plotted in Fig.5. As can be seen in Fig.5, the energy level of the dominant donor almost coincides with that of the *EL*2. Therefore, the dominant donor level may be identical to the *EL*2 level.

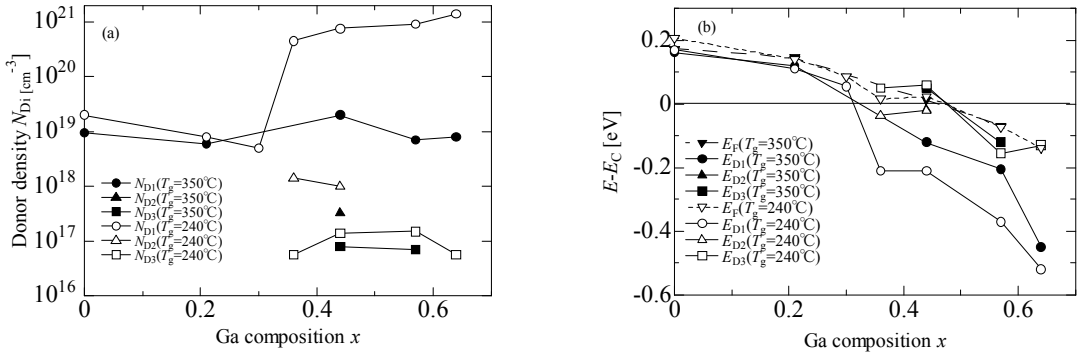

Fig.4 Dependence of (a) the densities and (b) the energies of donor levels on Ga composition.

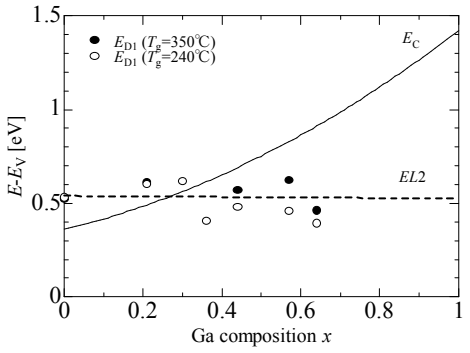

Fig.5 Ga composition dependence of the energy level E_{D1} of the dominant donor and the CBM with respect to the VBM.

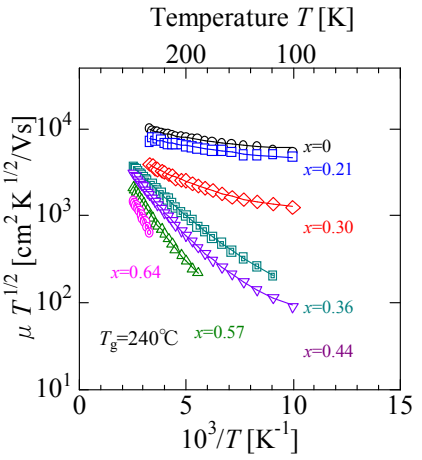

Fig.6 Arrhenius plots of $\mu T^{1/2}$.

Temperature dependence of electron mobility. The electric conduction in polycrystalline films is dominated in many cases by thermionic emission over potential barriers at grain boundaries. Then, the mobility can be expressed by the following expression with the mean value $q\bar{\phi}$ and the standard deviation qu of the barrier height when assuming the distribution in potential barrier height [7]:

$$\mu = Lq\left(\frac{1}{2\pi m^* k_B T}\right)^{\frac{1}{2}} \exp\left(-\frac{q\bar{\phi}}{k_B T} + \frac{q^2 u^2}{2k_B^2 T^2}\right), \tag{6}$$

where L is the grain size.

The logarithmic plots of $\mu T^{1/2}$ against the reciprocal of T are shown in Fig.6. The mean value and the standard deviation of the barrier height as well as the grain size L were obtained through fitting by Eq. (6). In Fig.6, the curves express the fitted results by Eq. (6). The Ga composition dependence of the mean value of the barrier height is shown in Fig.7. In Fig.7, the circles and the error bars express the mean values ($q\bar{\phi}$) and the standard deviations ($\pm qu$) of the barrier height, respectively. As can be seen in Fig.7, the barrier height is less than 20meV in the samples having lower Ga compositions than 0.21 while the barrier height increases with increasing Ga composition in the samples having higher Ga compositions than 0.30.

Fig.8 shows the Ga composition dependence of the estimated grain sizes L by the fitting. As can be seen in Fig.8, the estimated grain sizes L from Eq.(6) are comparable to the estimated mean grain radius r from AFM. This suggests the validity of applying the grain-boundary limiting model to the electron mobility.

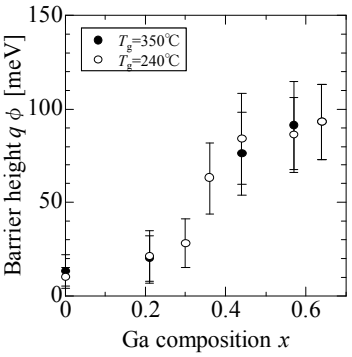

Fig.7 Ga composition dependence of barrier height.

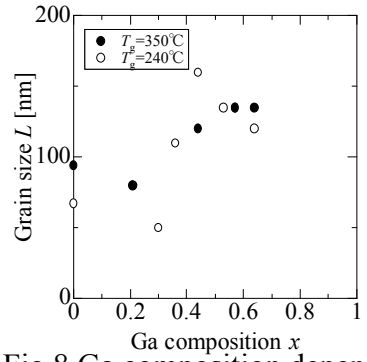

Fig.8 Ga composition dependence of grain size.

Summary

Polycrystalline $In_{1-x}Ga_xAs$ films were grown on glass substrates at 240 and 350 °C by molecular-beam deposition. Temperature dependences of the electron density and the electron mobility of the polycrystalline $In_{1-x}Ga_xAs$ films were investigated in order to study the mechanism of electric conduction.

The temperature dependence of the electron density can be explained by assuming three donor levels at the most. The density of the dominant donor level in the samples grown at 350 °C is almost independent of Ga composition. The density of the dominant donor level in the samples having Ga compositions of 0.36-0.64 grown at 240 °C was very high. The energy of the dominant donor level as well as the Fermi level decreased with increasing Ga composition. The energy level of the dominant donor coincides with that of *EL*2.

Being regardless of the substrate temperature, the temperature dependence of the electron mobility can be explained by thermionic emission over the barriers at the grain boundaries with the distribution of the barrier height taken into account. The barrier height is less than 20meV in the samples having lower Ga compositions than 0.21 while the barrier height increases with increasing Ga composition in the samples having higher Ga compositions than 0.30. Thus, the high electron mobilities in polycrystalline InGaAs having low Ga compositions are owing to the low barriers. As a result of the comparably high mobility and the larger band gap than InAs, InGaAs with a Ga composition around 0.2 is expected to be most suitable for high-speed TFTs.

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