PS-6-23

Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp212-213

Mobility Improvement Based on Mobility Model of Crystalline In-Ga-Zn-Oxide with High Indium Composition

Kazuhiro Tsutsui, Daisuke Matsubayashi, Noritaka Ishihara, Takako Takasu, Shinpei Matsuda and Shunpei Yamazaki

Semiconductor Energy Laboratory Co., Ltd.
398 Hase, Atsugi, Kanagawa, 243-0036, Japan
Phone: +81-46-248-1131, Fax: +81-46-270-3751, E-mail: kt1340@sel.co.jp

Abstract

In-Ga-Zn-O (IGZO), which is a widely researched and developed semiconducting material, has an electron mobility of approximately 5–10 cm^2/Vs. Its conduction mechanism is significantly different from that of single crystal silicon. We propose a new mobility model of an IGZO thin film having an In-rich composition in order to obtain an indicator for the field-effect mobility improvement and to clarify the detailed conduction mechanism.

1. Introduction

In-Ga-Zn-O (IGZO) was first synthesized by Kimizuka *et al*. in 1985 [1] and is now widely researched as a semiconducting material. C-axis aligned crystal (CAAC) IGZO is an oxide semiconductor whose crystal structure is aligned in the c-axis direction [2] as shown in Fig. 1. Since a CAAC-IGZO field-effect transistor (FET) exhibits high reliability [2] and has an extremely low off-state leakage current of several yocto (10^{-24}) amperes per micrometer [3], applications to low-power-consumption displays [4] and large-scale integration (LSI) circuits for nonvolatile memories [5] have been suggested.

The field-effect mobility is a critical factor that determines the performance of FETs for both display applications and LSI applications. In an FET using an IGZO thin film as an active layer, the interface scattering does not seriously affect the field-effect mobility; thus, there is a definite correlation between the field-effect mobility and the Hall mobility. This is why it is important to study fundamentally the Hall mobility of an IGZO thin film. In general, the electron mobility of IGZO is approximately 5–10 cm^2/Vs [3], and its Hall mobility increases with a temperature rise from low temperature to room temperature or higher. Another feature is that the Hall mobility increases with an increase in carrier density even in the degenerated region.

Having different valences and being irregularly arranged on the fixed sites in a $(Ga,Zn)O_2$ layer, the Ga^{3+} and Zn^{2+} cations serve as scattering factors like ionized impurities (Fig. 1). This phenomenon is called cation-disorder scattering [6]. In the IGZO thin film, the donor density, which may be attributed to hydrogen atoms trapped in oxygen vacancies [7], is at most approximately 10^{20} /cm^3. Since the donor impurity is an external factor, it is possible to control its density. In contrast, the density of the cations in the $(Ga,Zn)O_2$ layer is approximately 10^{22} /cm^3 and the Ga and Zn cations are included as part of the crystal structure of IGZO. That is, in the IGZO thin film, the cation-disorder scattering caused by the irregularly arranged Ga^{3+} and Zn^{2+} is a more critical limiting factor than the ionized-impurity scattering caused by donors. This fact indicates that the magnitude of the mobility of an IGZO thin film is not significantly influenced by the donor-impurity density.

In this report, for improvement in the mobility of an IGZO thin film, we discuss its theoretical mobility at room temperature and explain why an $In_3GaZn_2O_4$ thin film has a higher mobility than an $InGaZnO_4$ thin film.

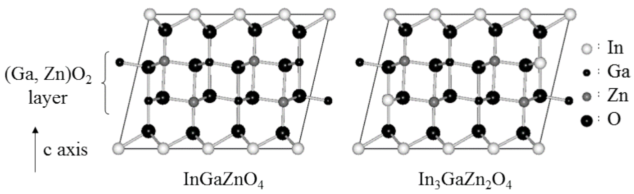

Fig. 1 Schematics of crystal structure of $InGaZnO_4$ (non-In-rich) and $In_3GaZn_2O_4$ (In-rich).

2. Experiment

It is generally known that the mobility of IGZO is improved as the proportion of In increases. We reported that an FET using a CAAC-$In_3GaZn_2O_4$ thin film as an active layer achieved relatively high field-effect mobility [8]. However, the mechanism for this is still uncertain. In a composition including a high proportion of In, such as $In_3GaZn_2O_4$, indium is also considered to be irregularly arranged on the fixed sites in the $(Ga,Zn)O_2$ layer; such a composition is referred to as In-rich composition (Fig. 1).

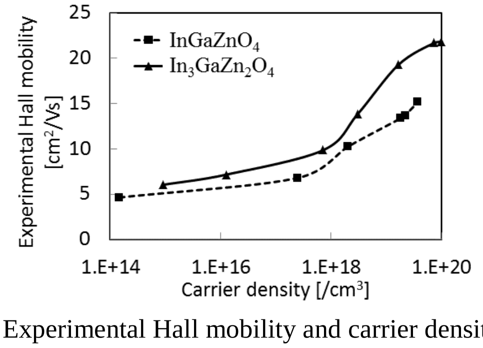

Fig. 2 Experimental Hall mobility and carrier density of In-rich IGZO thin film at room temperature. (Reference: non-In-rich $InGaZnO_4$ thin film.)

To examine the influence of the proportion of In on the mobility improvement in the In-rich composition, we measured the Hall mobility at various carrier densities. As shown in Fig. 2, the $In_3GaZn_2O_4$ thin film having an In-rich composition exhibits a higher Hall mobility than the $InGaZnO_4$ thin film having a non-In-rich composition.

3. Theory

To account for these experimental results, we expand the mobility model based on the cation-disorder scattering in the previous study [6] to a calculation model in which Ga, Zn, and In are irregularly arranged in the $(Ga,Zn)O_2$ layer. The ratio of the electron mobility of the IGZO thin film having an In-rich composition (μ_{InGaZn}) to that of the one having a non-In-rich composition (μ_{GaZn}) is calculated as follows:

$$\frac{\mu_{\mathrm{InGaZn}}}{\mu_{\mathrm{GaZn}}} = \frac{f_{\mathrm{Zn}}\, f_{\mathrm{Ga}}}{g_{\mathrm{In}}\left(g_{\mathrm{Ga}}\,(r_{\mathrm{In/Ga}}-1)^2 + g_{\mathrm{Zn}}\, r_{\mathrm{In/Ga}}{}^2\right) + g_{\mathrm{Zn}}\, g_{\mathrm{Ga}}} \times \frac{\rho_{\mathrm{GaZn}}}{\rho_{\mathrm{InGaZn}}}\left(\frac{\varepsilon_{\mathrm{InGaZn}}}{\varepsilon_{\mathrm{GaZn}}}\right)^2 \sqrt{\frac{m^*_{\mathrm{InGaZn}}}{m^*_{\mathrm{GaZn}}}} \qquad (1).$$

Here $f_{Ga\ (Zn)}$ and $g_{In\ (Ga,\ Zn)}$ denote the filling fraction of Ga (Zn) atoms in the $(Ga,Zn)O_2$ layer having a non-In-rich composition and that of In (Ga, Zn) atoms in the $(Ga,Zn)O_2$ layer having an In-rich composition, respectively. $r_{In/Ga} = \Delta Z_{In}/\Delta Z_{Ga}$ represents the ratio of the relative charge of In (ΔZ_{In}) to Ga (ΔZ_{Ga}) with respect to Zn. Furthermore, $\rho_{GaZn\ (InGaZn)}$, $\varepsilon_{GaZn\ (InGaZn)}$, and $m^*_{GaZn\ (InGaZn)}$ denote the cation density in the $(Ga,Zn)O_2$ layer, the relative dielectric constant, and the effective mass, respectively, in the non-In-rich composition (In-rich composition). The atomic filling fraction is (f_{Ga}, f_{Zn})=(1/2, 1/2) in the $InGaZnO_4$ thin film and (g_{In}, g_{Ga}, g_{Zn})=(1/4, 1/4, 1/2) in the $In_3GaZn_2O_4$ thin film. Figure 3 shows the dependence of the electron mobility ratio on the filling fraction of In atoms, which is obtained from Eq. (1).

In the case where the relative charge ratio of In to Ga is 1 or smaller than 1, the electron mobility of the $In_3GaZn_2O_4$ thin film, calculated from Eq. (1), ranges from 1 to 1.5 times that of the $InGaZnO_4$ thin film (region indicated by the arrow in Fig. 3). This result agrees with the experimental fact in Fig. 2 that the ratio of the Hall mobility of $In_3GaZn_2O_4$ to that of $InGaZnO_4$ ranges from 1 to about 1.4, when the mobility at substantially the same carrier density is compared with each other. Accordingly, this mobility model can qualitatively explain that an $In_3GaZn_2O_4$ thin film has a higher mobility than an $InGaZnO_4$ thin film.

Next, we examine how the atomic filling fraction and the relative charge ratio influence the mobility improvement. As shown in Fig. 3(a), the mobility is improved monotonically with increasing filling fraction of In atoms (except for g_{Ga}=1/4). Although this is the generally known experimental fact, the mobility model in the previous study [6] may not be able to explain it. Furthermore, as seen from Fig. 3(b), when the relative charge ratio of In to Ga is larger than 1 ($r_{In/Ga}$=1.3), in a certain range of filling fraction of In atoms, the mobility of the In-rich composition is lower than that of the non-In-rich composition. This means that the relative charge ratio is an important parameter for completely explaining the mobility improvement.

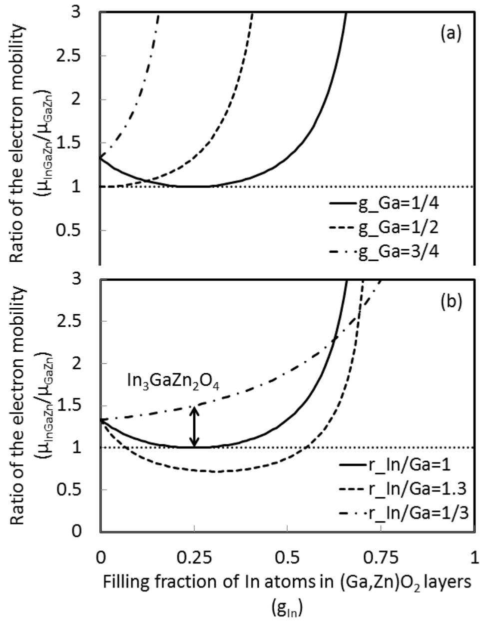

Fig. 3 Dependence of the ratio of the calculated electron mobility on the filling fraction of In atoms in In-rich IGZO thin film, with respect to (a) the filling fraction of Ga atoms and (b) the relative charge ratio.

4. Conclusions

We have proposed a new mobility model of an IGZO thin film having an In-rich composition. A qualitative explanation has been made for the fact that an $In_3GaZn_2O_4$ thin film has a higher mobility than an $InGaZnO_4$ thin film. Moreover, it has been theoretically indicated that the atomic filling fraction and the relative charge ratio have an influence on the mobility improvement.

References

[1] N. Kimizuka and T. Mohri, J. Solid State Chem. **60** (1985) 382.

[2] M. Takahashi *et al.*, Proc. AM-FPD Dig. Tech. Paper (2011) 271–274.

[3] K. Kato *et al.*, Jpn. J. Appl. Phys. **51** (2012) 021201.

[4] S. Yamazaki *et al.*, SID Symp. Dig. Tech. Papers. 43–1 (2012) 183–186.

[5] H. Inoue *et al.*, IEEE JSSC **47** (2012) 2258.

[6] Y. Kang *et al.*, Appl. Phys. Lett. **102** (2013) 152104.

[7] M. Nakashima *et al.*, J. Appl. Phys. **116** (2014) 213703.

[8] M. Hayakawa *et al.*, AMFPD'12 Digest (2012).