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A New Classification of Nano-Scale Crystallinity of In-Ga-Zn-Oxide Films

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Abstract

We have reported that, in semiconductor devices based on In-Ga-Zn-O (IGZO), the crystallinity of IGZO is associated with the reliability of the devices. Therefore, evaluation and classification of the crystallinity is important. In this study, we evaluated nano-scale crystallinity of IGZO films deposited by various conditions, and found the relationship between nano-scale crystallinity and physical properties related to the reliability, so that we propose a new classification of the crystallinity of IGZO.

1. Introduction

Oxide semiconductors (OS) such as In–Ga–Zn–O (IGZO) have been under extensive research and development as next-generation semiconductor materials. OS transistors are researched and developed for many applications such as energy-efficient displays that have already reached the commercial production stage [1], as well as nonvolatile memory and central processing units [2]. The crystallinity of IGZO thin film largely affects device characteristics, especially reliability. We discovered highly crystalline structure of IGZO named *c*-axis aligned crystalline IGZO (CAAC-IGZO) [3]. We successfully fabricated highly reliable devices, by using CAAC-IGZO for the active layer of transistors,

In addition, we found a nano-crystalline (nc) IGZO distinguishable from amorphous IGZO [4]. We analyzed nano-beam electron diffraction (NBED) patterns of samples fabricated under various sputtering conditions, and observed diffraction patterns distinguishable from halo patterns in the samples that showed no definite lattice structure in transmission electron microscopy (TEM) images. As a result, we found that structures of low-crystallinity IGZOs are classifiable in detail.

Figure 1 and Table I show experimental data that we previously obtained from IGZO thin films with different crystallinities and densities (CAAC-IGZO, nc-IGZO, and low-density nc-IGZO) by a constant photocurrent method (CPM) measurement [5]. The low-density nc-IGZO has lower crystallinity and lower density than "standard" nc-IGZO. The degree of the crystallinity of these nc-IGZOs depends on differences fabrication process, such as sputtering gas pressure and sputtering power. Similarly to "standard" nc-IGZO and CAAC-IGZO, the low-density nc-IGZO exhibits a diffraction pattern distinguishable from a halo pattern in NBED observation using an electron beam of 1 nm in diameter. As shown in Fig. 1, light absorption due to defect levels measured by CPM increases as crystallinity decreases. Many studies reported that the deep-level density of states (DOS) affects reliability, especially photo-induced negative-bias temperature stress (PNBTS) durability, of field-effect transistors (FET) [5]. In other words, high crystallinity should provide low DOS and high reliability. Accordingly, detailed evaluation and classification of crystallinity of IGZO films are of great industrial demand.

In this study, the crystallinity and physical properties of IGZO films deposited using different methods were evaluated. We have found that a difference of crystallinity of an IGZO film greatly affects electrical properties of the film and reliability of the device using the film.

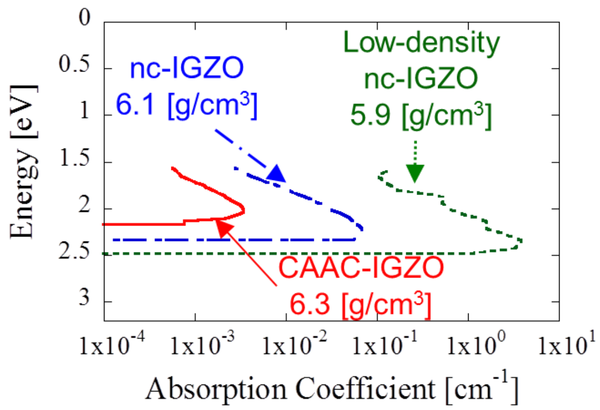

Fig. 1 Light absorption due to defect levels in IGZO films measured by CPM

Table I Absorption Coefficients of IGZO Films

	CAAC-IGZO	nc-IGZO	Low-density nc-IGZO
Absorption coefficient at the sub-gap state [cm^{-1}]	5.8×10^{-4}	1.6×10^{-2}	5.3×10^{0}

2. Experiment

IGZO thin films were deposited on a Si wafer with a 100-nm-thick SiO_x film. The films were fabricated by pulsed laser deposition (PLD) or magnetron sputtering using a polycrystalline In–Ga–Zn–O (In:Ga:Zn = 1:1:1) target. In PLD, we used a Nd:YAG laser (with a wave-length of 266 nm, a laser frequency of 10 Hz, and

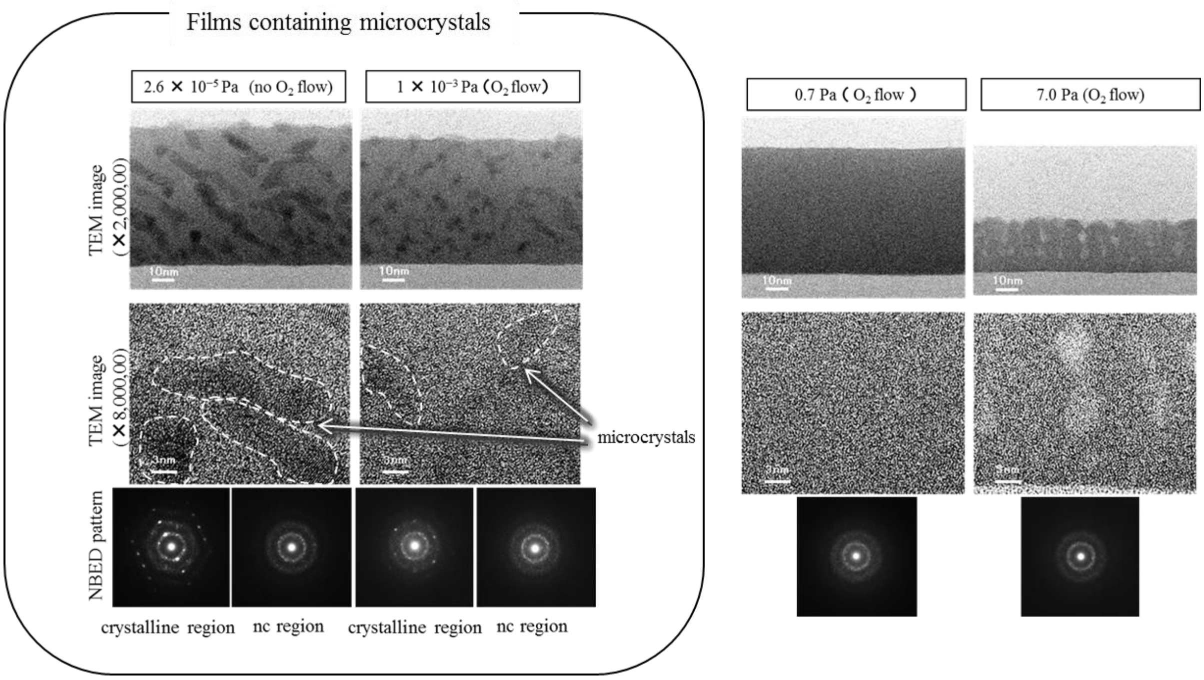

Fig. 2 Cross-sectional TEM images (top, middle) and 1-nm ϕ NBED patterns (bottom) of PLD- IGZO films. Two thin film IGZO samples on the left contain microcrystals.

laser power of 0.1 W). The pressures during IGZO film deposition were 2.6 × 10^{-5} Pa (base pressure), 1 × 10^{-3} Pa, 0.7 Pa, and 7.0 Pa (oxygen pressure). In the sputtering, the crystallinity of IGZO thin films systematically changed with increasing gas pressure in the deposition chamber. In this experiment, the samples were not annealed. The crystallinity was evaluated by X-ray diffraction (XRD), cross-sectional TEM observation, and NBED. In this evaluation, we used an electron beam with a minimum diameter of 1 nm. We also evaluated the physical properties including electrical characteristics.

3. Result and Discussion

Figure 2 shows cross-sectional TEM images of the IGZO films deposited by the PLD method. We can see that the films deposited in high vacuum conditions (2.6 × 10^{-5} Pa and 1 × 10^{-3} Pa) contain microcrystals. It is well known that clusters are ejected from a target [6] and the mean free path of them becomes longer in the higher vacuum condition. Therefore, the microcrystals are observed in the cross-sectional TEM images of the films deposited in the high vacuum conditions. On the other hand, uniform films were deposited under the pressure of 0.7 Pa, although voids where the density is low appear in the film deposited under the higher pressure of 7.0 Pa. In the films deposited under these high pressure conditions, the microcrystals are not observed. A similar tendency regarding the existence of microcrystals is confirmed also by XRD.

NBED patterns of the films are depicted at the bottom of Fig. 2. The diffraction pattern of the microcrystal regions in the low-pressure deposited films indicates the presence of $In_2Ga_2ZnO_7$ crystals. A spot-like diffraction pattern is observed from NBED in the regions where microcrystals are not clearly found in TEM images. This result implies that this region belongs to nc-IGZO on the basis of the definition of nc-IGZO. Furthermore, NEBD patterns of the films deposited under the high presser conditions of 0.7 Pa and 7.0Pa also show the spot-like diffraction pattern. From these result, nc-IGZO is essentially different from the microcrystals that are contained in IGZO thin films, and is distinguished from the conventional amorphous IGZO [7]. Differences in electrical characteristics between FETs fabricated using those films with different crystallinities, and the film structure surrounding microcrystals, which is still under controversial discussion, will be presented at the conference.

4. Conclusions

The crystallinity and physical properties of IGZO films deposited using different methods were evaluated. Then we confirm that the difference of nano-scale crystallinity in IGZO thin films is related to physical properties which are responsible for device reliability. Therefore we emphasize the importance of the precise classification of crystallinities of IGZO.

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