Electronic Structures and Defects Analysis of Amorphous Oxide Semiconductor toward IGZO Display Application

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ABSTRACT

I am very honored to receive the 2022 Peter Brody Prize for my research on amorphous oxide semiconductors and contributions to display applications. The citation title was "for his pioneering research on defect analysis of amorphous oxide semiconductors (AOSs) and developments of novel active-matrix displays (AMDs) using indium gallium zinc oxide (IGZO)". I am grateful to the many people who supported me to conduct the research. In this presentation, I look back on my decade of work on IGZO technology and present my prospects.

1 Introduction

Amorphous oxide semiconductors (AOSs) are high-performance semiconductors that can be fabricated even on glass/plastic substrates. Among various AOS materials, amorphous In-Ga-Zn-O (a-IGZO) was first demonstrated as a channel of thin-film transistors (TFTs) in 2004.[1] Since then, several manufacturers had demonstrated prototypes, including transparent displays, flexible displays, and organic light emitting diode displays, as summarized in previous many review articles.[2] Eventually, the IGZO TFTs with a nominal chemical composition of $InGaZnO_4$ (so-called 111 compositions) were utilized in commercial displays. This is likely because the 111 compositions of IGZO have been the most intensively studied and well understood about its defect, and has a sufficient process window for large area production of TFT backplanes.

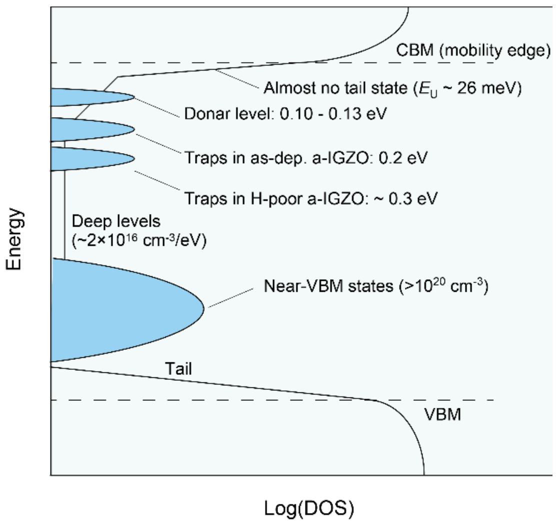

Fig. 1 Electronic structure of a-IGZO with subgap defects reported so far

Before starting mass production, the main concern in this field was the long-term stability of IGZO TFTs. Various defects related to the stability have been identified and proposed at that time, including oxygen deficiency, weakly bonded/excess oxygen, hydrogen, metastability of the amorphous structure, and so on.[3] These defects are closely related to the performance, hysteresis, and instability of TFT. In this abstract, I will quickly review some findings on the defects in AOS.

2 Defects in amorphous oxide semiconductors

The conductivity of transparent oxide conductors such as indium tin oxide (ITO) can be controlled by the amount of oxygen supply to the chamber during the sputtering process. Similarly, the carrier concentration of a-IGZO is largely affected by the oxygen flow rate ratio (R_{O2}) during sputtering deposition as shown in Fig.2(a). a-IGZO films deposited at R_{O2} = 1% show degenerate conduction with a high carrier concentration of >10^{19} cm^{-3}, whereas the carrier concentration is greatly suppressed at R_{O2} = 10%, to be <10^{13} cm^{-3}. To understand oxygen-related defects, it is important to look at both extreme cases. For example, we can see the big difference in the absorption coefficient of a-IGZO films deposited under various R_{O2}. The subgap optical absorption and free carrier absorption increases with decreasing R_{O2}. The a-IGZO film deposited without oxygen supply (R_{O2} = 0%) shows strong absorption over the entire visible region, resulting in a dark-colored film. We found that the segregated indium metal is the cause of the strong absorption confirmed by x-ray photoelectron spectroscopy. On the other hand, if we use too high R_{O2}, excess oxygen can be incorporated into the film and form an electron trap. Such defects can behave as a negative-U like trap states

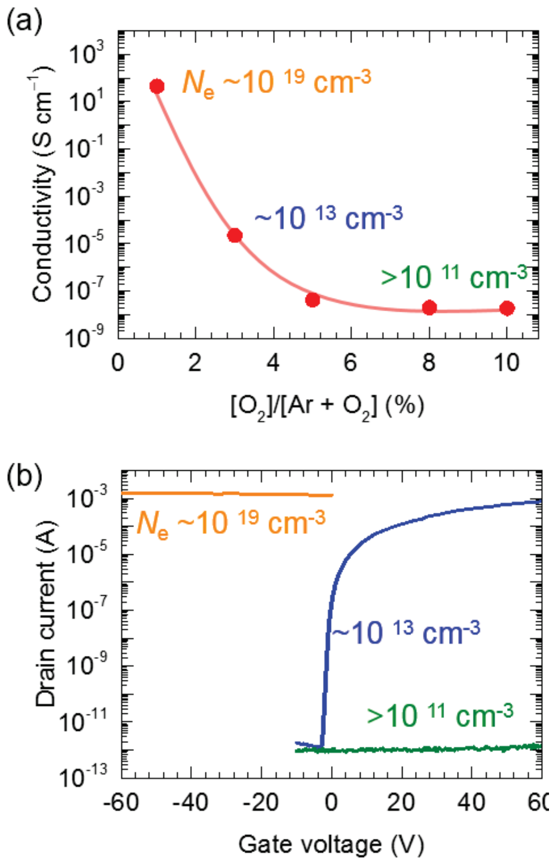

Fig. 2. (a) Conductivity change as a function of oxygen flow ratio (R_{O2}). (b) Transfer curves of unannealed a-IGZO TFTs corresponding to R_{O2} = 1, 3, and 8% in (a).

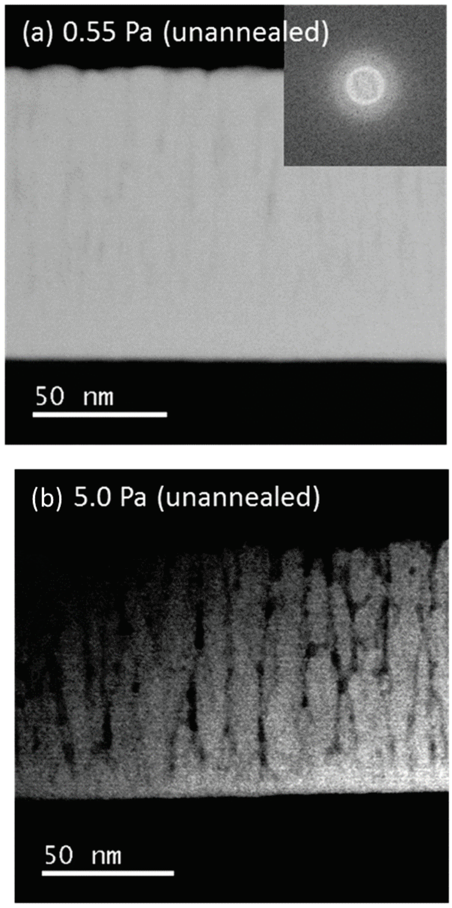

Fig. 3. HAADF-STEM images for (a) high-density film and (b) low-density film prepared by different deposition pressure.

and cause bistability and large hysteresis in TFT operation resulting in extreme threshold voltage. Therefore, both oxygen deficiency and excess oxygen should be minimized by finely tuning the deposition condition to make practical IGZO TFT.

The microstructure of the a-IGZO films also has a large impact on the device's performance. X-ray reflectivity measurement revealed that the film density decreased from 6.1 to 5.5 g/cm^3 with increasing total pressure (P_{Tot}) during the sputtering process. Interestingly the lowest film density is almost 10% smaller than that of the optimized a-IGZO films. But it hardly imagines that the usual packing structures of ionic bonds can produce such low-density structures. Then we employed HAADF-STEM observation to see the void structure because high-contrast images according to the atomic numbers of the constituent elements can be obtained. It is confirmed that low-density a-IGZO film has a very inhomogeneous structure. The film density of IGZO film largely affects the TFT characteristics. Low-density TFT deposited at the high P_{Tot} led to poor TFT with the extraordinarily high threshold voltage and low on-current. From TDS measurement for this low-density film, it is confirmed that this low-density film contains a lot of excess oxygen. These results provide the caution that P_{Tot} must be optimized to produce a high-density film, and high P_{Tot} conditions should not be employed to make practical IGZO TFT.

3 Conclusion

Some important defects to understand AOS materials were presented in this abstract. Several other defects have been clarified in the past decade. However, instability issues are still not satisfactorily solved, especially for the next generation of electronics such as transparent/flexible applications. A deeper investigation of those defects is necessary and it would lead to the development of new functional AOS materials as well.

References

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