M-8-1 (Invited)

Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp1098-1099

Properties and Application of Crystalline In-Ga-Zn-Oxide Semiconductor

Shunpei Yamazaki

Semiconductor Energy Laboratory Co., Ltd., 398 Hase, Atsugi-shi, Kanagawa, 243-0036, Japan.
Phone : +81-46-248-1131 Fax : +81-46-270-7227, E-mail : yamazaki@sel.co.jp

Abstract

The crystalline IGZO film which we developed has CAAC, a novel crystal structure without clear grain boundaries. Transistors using CAAC-IGZO have little variation in characteristics and high reliability even with a short channel length. Application of the CAAC-IGZO to various LSI devices is expected.

1. Introduction

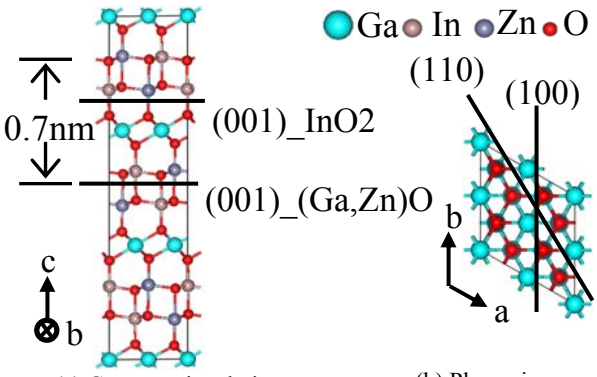
IGZO technology has been implemented on SHARP's smartphones "AQUOS PHONE ZETA SH-02E", jointly developed by SEL and Sharp Corporation. It was the first practical use of IGZO technology after thirty years since the first synthesis by Dr. Noboru KIMIZUKA in 1985 [1].

The IGZO has a novel crystalline structure, CAAC (C-Axis Aligned Crystal) [2]. With an extremely small off-state leakage current of 10^{-24} A/μm (1yA/μm at RT) and an on/off ratio of 20 digits [3, 4], off-state characteristics of CAAC-IGZO are by far superior to those of Si materials.

This paper will examine the mechanism of forming a CAAC-IGZO film and elucidate transistor characteristics of CAAC-IGZO with deep submicron scaling.

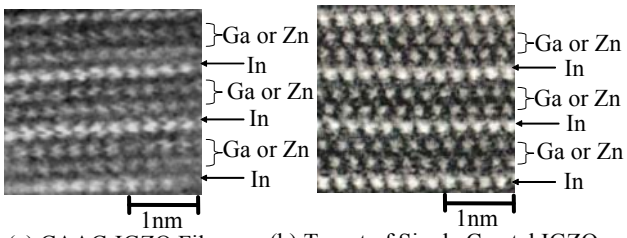
2. Structure of CAAC

Fig. 1 shows an atomic model of single crystal IGZO. Its homologous structure has cleavage energies. A plane with extremely small cleavage energies exists on (001)_(Ga, Zn)O. In sputtering deposition, when Ar or O ions collide with a polycrystalline IGZO target, a pellet (cleavage unit) of about 0.7 nm thick is formed by cleavage at the cleavage surface. Consequently, in Fig. 2, a TEM image of the IGZO film shows the identical structure as the IGZO target.



(a) Cross sectional view (b) Plane view

Fig.1 Hexagonal crystalline IGZO（homologous structure）



(a) CAAC-IGZO Film (b) Target of Single Crystal $IGZO_4$

Fig.2 HAADF-STEM Images of CAAC and Sputter Target

Fig. 3(a) is a schematic model of CAAC formation. A pellet flies onto the substrate surface where the pellet migrates and recombines with another pellet by collision. In this manner, pellets are laterally-connected and stacked in a thickness direction. Extremely small cleavage energy on the plane (001)_(Ga, Zn)O is calculated in Fig. 3(b).

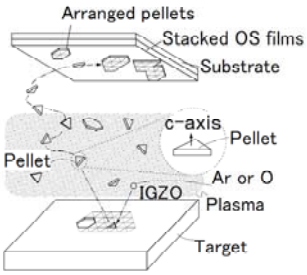
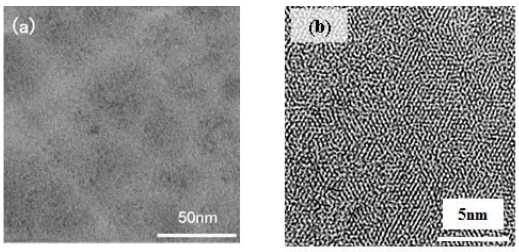


Fig. 3(a) Model of CAAC Formation

Plane Structure	Cleavage Energy (J/m^2)
(100)	2.12
(110)	2.18
(001)_InO_2	2.60
(001)_(Ga,Zn)O	0.68 (Min)

Fig. 3(b) Calculation Results of Cleavage Energy

Fig. 4(a) is a macro-plane TEM image of CAAC-IGZO film. Even with shading due to thickness variation, grain boundaries are not clearly observed. Fig. 4(b) shows hexagonal crystals clearly aligned with each other.



(a) Plane TEM Image of CAAC-IGZO Film (b) Plane HR (high resolution) TEM Image of CAAC-IGZO Film (enlarged image of (a))

Fig.4 Comparison of the Structures of Crystal Boundaries in Plane TEM Images

In addition, measurement by CPM (constant photo-current method) showed that DOS (density of states) of CAAC-IGZO film is approximately 1/1000 of that of an oxide semiconductor having a so-called amorphous structure [5].

3. Transistor Characteristics

Fig. 5 shows variations in transistors using a CAAC-IGZO film. There was little variation among the 25 (5×5) transistors on a 5-inch square substrate. The transistors were normally-off with L=0.19μm, W=1.0μm, Tox=20nm. The characteristics were Vth: 0.79V, Vth(3σ): 63mV, S-value (Ave): 109mV/dec., μ(Ave): 7.7cm^2/Vs.

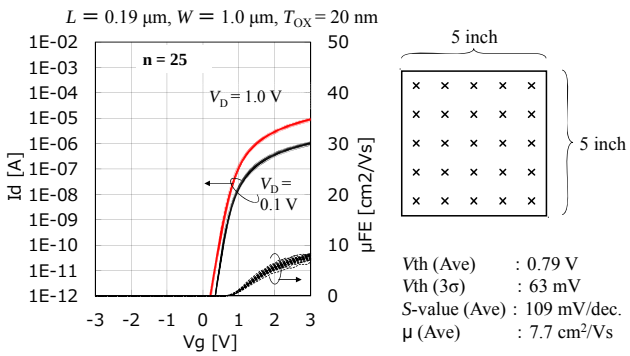


Fig.5 Variation in Characteristics of CAAC-IGZO Transistors

In Fig. 6, the horizontal axis represents the channel length L while the vertical axis represents Vth and μFE. The channel length L was changed in the range of 0.19μm to 10μm. The threshold voltage is constant without depending on the channel length L. Similar results will be expected even with the channel length L of 100nm or less.

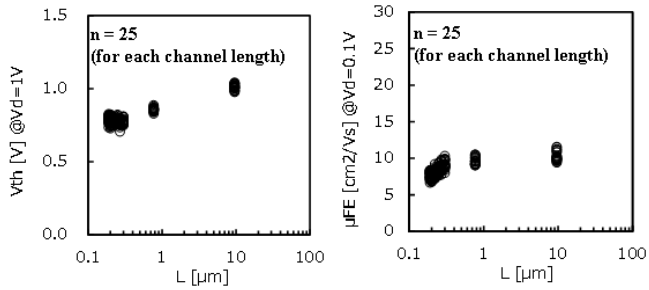


Fig.6 Dependence of Characteristics of CAAC IGZO Transistors (L = 0.19 to 10μm, W = 1μm) on Channel Length

Fig. 7 shows results of BT tests (under 125°C, 12hr) (+GBT, -GBT) on the transistors (L=0.8μm, W=10μm, Tox=20nm). Further, HCI (hot carrier injection) was performed. Even though the further investment is required, the LSI specifications have been satisfied. Therefore, in terms of reliability, CAAC-IGZO transistors can be introduced into Si-LSI and be formed three-dimensionally through wirings above CMOS. Table 1 shows basic parameters of CAAC-IGZO.

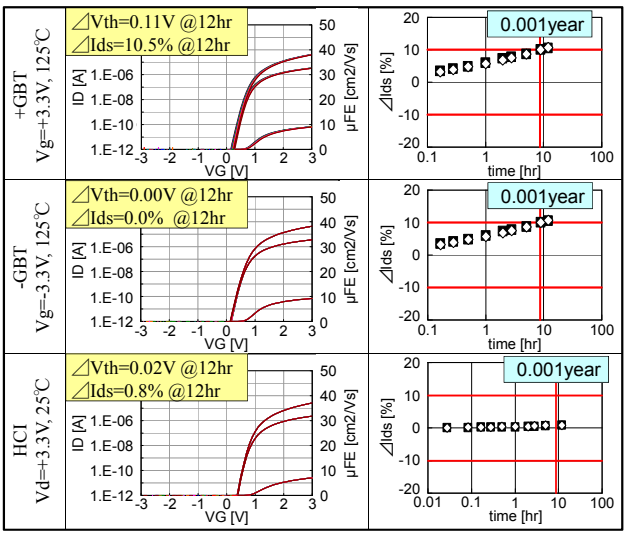


Fig. 7 Reliability Measurement Results

Table. 1 Summary of Features of CAAC-IGZO

	CAAC-IGZO (intrinsic)	Si (intrinsic)
Eg→wide	2.8 to 3.2 eV	1.1 eV
Minority carrier (hole)	< 10^{-9} cm^{-3}	10^{11} cm^{-3}
Majority carrier (electron)	Injection from only source of TFT	
Avalanche breakdown	non	occurs
Debye Length	> 1 m	μm order
Reliability	as high as Si LSI	
Off-state current	yA/μm order at 85°C	pA/μm order
Small S value, close to an ideal value	60 to 100 mV/dec.	
On/off ratio	> 10^{20}	10^{6} to 10^{10}

3. Conclusion

The most remarkable is that the carrier concentration of CAAC-IGZO in an intrinsic state is extremely small, 1/10^{20} of that of Si. In addition, the debye length of the CAAC-IGZO is the order of m while that of Si is the order of μm. In theory, CAAC-IGZO can have extremely small S-value. Thus, an extremely small short-channel effect and an increased CBL (conduction band leveling) effect are expected. The above-described characteristics (with a high on/off ratio and extremely small off-state leakage current, and without clear crystal grain boundaries) enable application of CAAC-IGZO to various LSI devices.

References

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

[2] J. Koezuka *et al.*, SID Symposium Digest, **44**, (2013) 723.

[3] S. Yamazaki, presented at the Int. Workshop Private Sector Academia Interactions (2011).

[4] M. Murakami *et al.*, *Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials* (2012) 320.

[5] S. Yamazaki *et al.*, SID Symposium Digest, **43**, (2012) 183.