Sputtering Target of Oxide Semiconductor with High Electron Mobility and High Stability for Flat Panel Displays

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Metal oxide semiconductors are expected to be used for the thin film transistor (TFT) of large high-definition flat panel displays (FPDs) and In-Ga-Zn-O (IGZO), in particular, is already being mass-produced. For high-definition 8K FPDs, we have developed a new metal oxide semiconductor with a high electron mobility. Semiconductors used as a film in a TFT are made of oxide ceramics. We sintered the new metal oxide ceramic, In-W-Zn-O, as the base material of the new metal oxide semiconductor film and studied the properties of a TFT that used the new metal oxide semiconductor. The electron mobility of In-W-Zn-O was three times higher than that of IGZO and the stability of a TFT with In-W-Zn-O was superior to that of one with IGZO. In-W-Zn-O sintered material showed a high density and a low electrical resistivity, indicating that it is suitable as a sputtering target. This development will lead to the realization of 8K FPDs.

Keywords: sintered oxide ceramics, thin film transistor, In-W-Zn-O, field-effect mobility

1. Introduction

A flat panel display (FPD) has thin film transistors (TFTs)*1 placed in each of its pixels to control the brightness of the red, green, and blue colors in each pixel. Owing to the trend towards higher-resolution FPDs, from full high definition (FHD) to 4K and 8K,*2 the industry needs a material with high electron mobility*3 as the semiconductor layer of TFTs.(1) Table 1 shows an overview of semiconductor materials used for TFTs, summarizing information presented at academic conferences.(2)-(4) The most widely used material is a-Si.*4 Due to its low electron mobility, a-Si is reported to be not readily adaptable to 8K. With low-temperature polysilicon (LTPS),*5 it is difficult to form a film on large glass substrates and its manufacturing cost is high. In comparison, the oxide semiconductor that Hosono et al. proposed(5) in 2004 is reported to permit upsizing similar to a-Si and is being adapted to mass production. This oxide semiconductor is an In-Ga-Zn-O-based material (known as IGZO). Its electron mobility is approximately 10 cm^2/Vs. Higher electron mobility than this is required for use in 8K televisions. In sum, a material that offers both high mobility and stability comparable to IGZO is sought for mass production.

Sumitomo Electric Industries, Ltd. has worked on the development of such a material, taking note of In-W-O,(6),(7) a high-mobility material reported by National Institute for Materials Science. Oxide semiconductors provide electrons due to oxygen vacancies. To use an oxide semiconductor in a TFT, it is necessary to control the amount of oxygen vacancies within an optimal range. The bond dissociation energy between tungsten and oxygen is higher than that between gallium and oxygen. Therefore, a trace amount of tungsten is highly effective in reducing oxygen vacancies. This implies that the resultant potential for a relatively, higher content of the element indium, which forms electron conduction paths, can improve the mobility.

Table 1. Various semiconductor materials for FPDs

		Semiconductor Material for TFT		
		a-Si	LTPS	Oxide semiconductor
TFT characteristics	Electron mobility (cm^2/Vs)	< 1	30-100	10-30
	Stability	Low	High	Med.
	Leak current (A/μm)	10^{-13}	10^{-12}	10^{-16}
Manufacturability	Suitable substrate size (m)	2.9 × 3.1 (G10 <)	1.5 × 1.9 (G6)	2.2 × 2.5 (G8)
	Number of photo-mask used for manufacturing	4-6	5-9	4-6
	TFT characteristics uniformity	High	Low	High

The oxide semiconductor layer used in TFTs is formed by sputtering,*6 and sintered oxide ceramic is used as a sputtering target. Using a powder metallurgy technique, we fabricated a sputtering target made of sintered oxide ceramic. Subsequently, a TFT incorporating this target was made and evaluated. The developed sputtering target has proven to be effective in exerting excellent TFT characteristics.

2. Development of Sintered Oxide Body

While its high mobility has been reported in existing papers, it has been difficult to form the In-W-O sputtering target into a high-density sintered body. Although sintering of In_2O_3 progresses at approximately 1,500°C, tungsten oxide, which decomposes and vaporizes at approximately 1,200°C, disperses before sintering is completed. To ensure that sintering is completed before the tungsten evaporates, we explored what element would form a low-melting-point tungsten compound. Taking note of the melting point of approximately 1,200°C of $ZnWO_4$, we tested the idea of adding ZnO to In-W-O. The result was reduced evaporation of tungsten and a high-density sintered body, obtained through the successful progress of sintering owing to the melting of $ZnWO_4$ at 1,200°C. Table 2 presents the properties of the sintered In-W-Zn-O body. This was a low-electrical resistivity sintered body that enabled DC sputtering. As the next step, using the obtained sintered body, we formed a TFT and evaluated its characteristics.

Table 2. Properties of sintered material developed by Sumitomo Electric

	Material developed by Sumitomo Electric	Conventional material
Constituent elements	In-W-Zn-O	In-Ga-Zn-O
Sintering density (%)	98 <	98 <
Electrical resistivity (Ωcm)	$\leq 10^{-2}$	$< 10^{-2}$

3. Characteristics of TFT Made of Newly Developed Target

3-1 Use of newly developed target for TFT fabrication

A low-electrical resistivity silicon wafer provided with a thermally oxidized SiO_2 film, a thickness of 200 nm, was used as a substrate. A stencil printing approach incorporating metal masks was followed to make the TFT.

First, an In-W-Zn-O film was formed as a semiconductor layer with a metal mask placed on the substrate. To form the semiconductor layer, the sintered In-W-Zn-O body developed by Sumitomo Electric was used as a sputtering target. The target size was two inches in diameter, the sputtering power was 60 W, the distance between the substrate and the target (ST) was 90 mm, the pressure was 0.5 Pa, the total gas flow rate was 30 sccm, and the partial pressure of oxygen (p_{O2}) was 10% or 20%. The semiconductor layer was formed to a thickness of 30 nm. Next, using another metal mask, metal molybdenum layers were formed to serve as source (S) and drain (D) terminals. For sputtering conditions, an argon atmosphere was used, the pressure was 1 Pa, the radio frequency (RF) power was 200 W supplied to Molybdenum target with four inches diameter, the ST distance was 90 mm, and the film thickness was 100 nm. The passivation layers were comprised of a SiO_2 film formed by the plasma enhanced chemical vapor deposition (PECVD-SiO_2 film) and an Al_2O_3 formed by the sputtering process (SP-Al_2O_3 film) after the deposition of S and D terminals. The PECVD-SiO_2 film was formed to a thickness of 200 nm using a SiH_4-N_2O gas mixture. Contact holes were formed through reactive ion etching (RIE). The SP-Al_2O_3 film was formed to a thickness of 200 nm, using a metal (aluminum) target with the diameter of four inchies, a partial p_{O2} of 25%, a pressure of 1 Pa, and RF power of 200 W. Contact holes were formed through the lift-off process. After the RIE and lift-off processes, the sample was annealed at 350°C for 1 hour in a nitrogen atmosphere. Figure 1 provides a top-view and a cross-sectional view of the produced TFT. Using the substrate Si wafer as a gate terminal, the channel width (W) and length (L) were set to 1,000 μm and 350 μm, respectively.

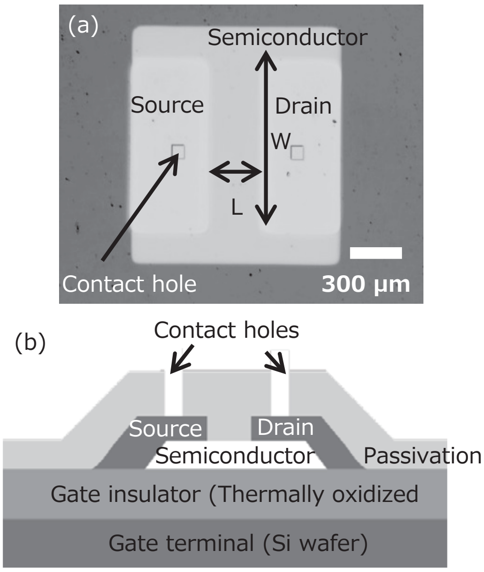

Fig. 1. TFT structure
(a) Top-view and (b) Cross-sectional view of TFT

Using the semiconductor device parameter analyzer B1500A (manufactured by Keysight Technologies), we evaluated the characteristics of the TFT. Stress conditions used in the stability test (NBS/PBS)*[7] were $V_{ds} = \pm 30$ V, room temperature, dark place, and 3,600 s stress duration.

3-2 Basic characteristics of TFT made of newly developed In-W-Zn-O materials

Table 3 summarizes the characteristics of the TFT with the passivation layer made of PECVD-SiO_2. The output characteristic at $V_{ds} = 0$ V was favorable, being close to $I_{ds} = 0$ A [Fig. 2 (a)]. The transfer characteristics [Fig. 2 (b)] were a mobility of 35 cm^2/Vs, at $V_{ds} = 0.1$ V, V_{th}*[8] = 0.8 V, at $V_{ds} = 5.1$ V and a sub-threshold swing (SS) value*[9] of 0.08 V/decade at $V_{ds} = 5.1$ V. This high mobility surpassed that of IGZO (In : Ga : Zn = 1 : 1 : 1) of 10 cm^2/Vs. Moreover, at similar levels of those of IGZO, the newly developed TFT achieved a V_{th} close to 1 V and a low OFF-state current.

Figure 3 shows the dependence of mobility and of V_{th} on the partial p_{O2} in the In-W-Zn-O film deposition. The mobility remained high and V_{th} exhibited a constant level against changes in the partial p_{O2} during film deposition. This implies that the TFT characteristics were not susceptible to oxygen concentration variation, if any, in the sputtering deposition equipment. This feature is considered advantageous for suppressing variation of the characteris-

Table 3. Characteristics of TFT incorporating newly developed target (Passivation layer: PECVD-SiO_2)

		IGZO	In-W-Zn-O by Sumitomo Electric
Field-effect mobility (cm^2/Vs)		10	35
V_{th} (V)		≃ 1.0	0.8
Stability: ΔV_{th} (V)	PBS	2.00 <	0.40
	NBS	0.10 <	0.07

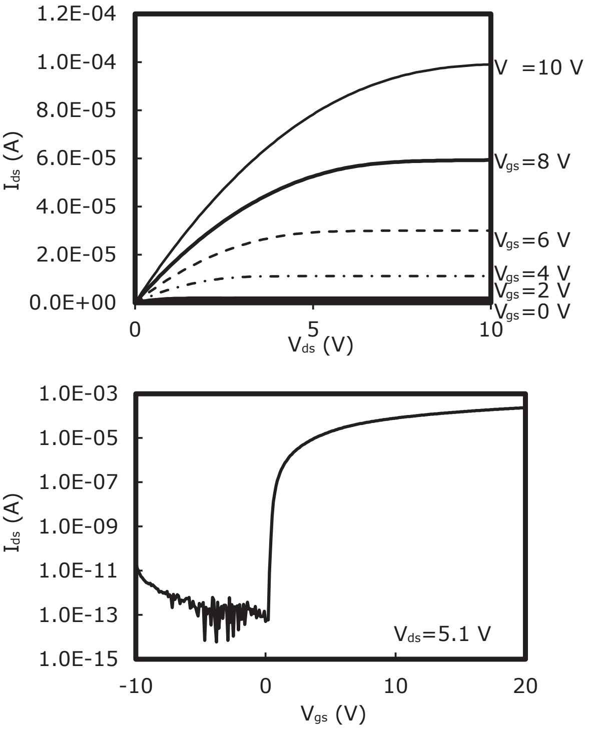

Fig. 2. TFT characteristics
(a) Output curve, (b) Transfer curve

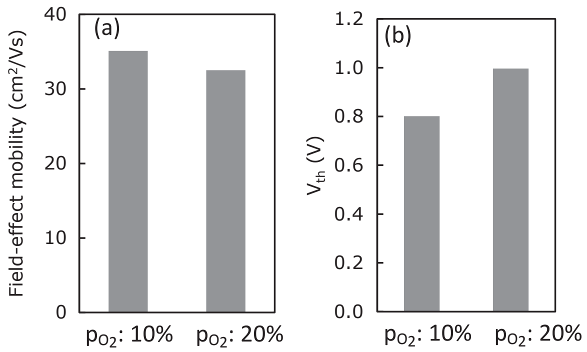

Fig. 3. Effects of partial p_{O2} during film deposition on TFT characteristics

tics of the TFT placed on the surface of a large glass substrate.

We also conducted NBS and PBS stability tests to evaluate the degradation characteristics of the TFT against repeated driving. Figure 4 presents transfer characteristics at 0, 1,200, 2,400, and 3,600 s during the NBS and PBS tests. The NBS test revealed that the V_{th} remained virtually constant against increasing stress time, with the magnitude of shift in V_{th} being 0.07 V. In the PBS test, the magnitude of shift in V_{th} was 0.40 V towards the positive side. Using IGZO, we conducted similar testing. In NBS, V_{th} shifted by 0.10 V, while in PBS, V_{th} shifted by 2.00 V. Thus compared with IGZO, In-W-Zn-O developed by Sumitomo Electric exhibited better performance.

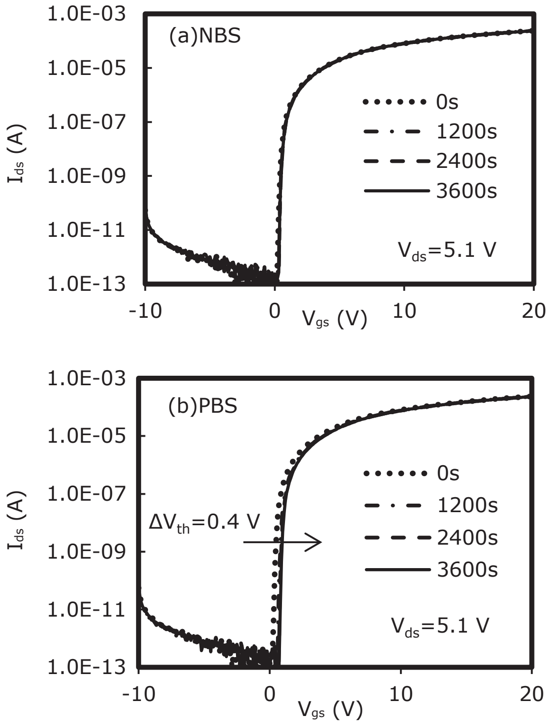

Fig. 4. Changes in characteristics during stress test

3-3 Annealing resistance of newly developed In-W-Zn-O material

We inspected how the TFT characteristics were affected by increasing annealing temperature. Figure 5 shows the dependence of mobility of IGZO and In-W-Zn-O on the annealing temperature, with their passivation layers made of SP-Al_2O_3. Annealing was performed in an atmospheric environment at each of the temperatures indicated in the figure for 1 hour. The mobility of IGZO decreased with increasing annealing temperature, while that of In-W-Zn-O did not decrease.

Next, we tested the dependence of mobility of In-W-Zn-O on the annealing temperature, with the protective layer made of a PECVD-SiO_2 film. The results are shown in Fig. 6. A nitrogen atmosphere was used for this

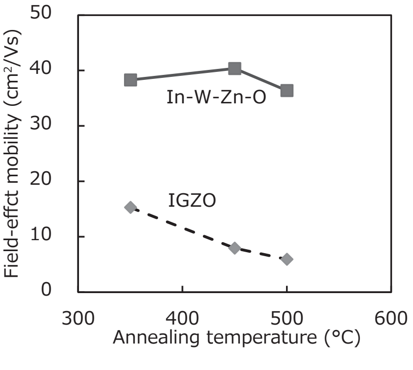

Fig. 5. Annealing temperature dependence of mobility
(Passivation layer: SP-Al_2O_3)

annealing, which was performed at each of the temperatures indicated in the figure for 1 hour. The mobility did not decrease despite increases in the annealing temperature. Figure 7 illustrates the magnitudes of shift in V_{th} observed during NBS and PBS of up to 450°C. The stability improved with increasing annealing temperature, as revealed by decreases in the magnitude of shift in V_{th}.

The results presented above prove the high temperature resistance of In-W-Zn-O without decreasing in mobility, in contrast to the decreasing mobility of IGZO with increasing annealing temperature. In light of the exceptionally high stability required for use in organic EL displays, In-W-Zn-O is superb due to its potential of achieving high stability making use of a high annealing temperature, and of retaining a high mobility against such a high annealing temperature.

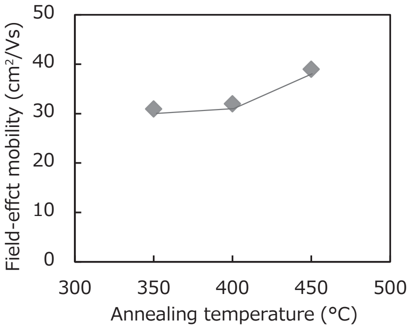

Fig. 6. Annealing temperature dependence of mobility (Passivation layer: PECVD-SiO_2)

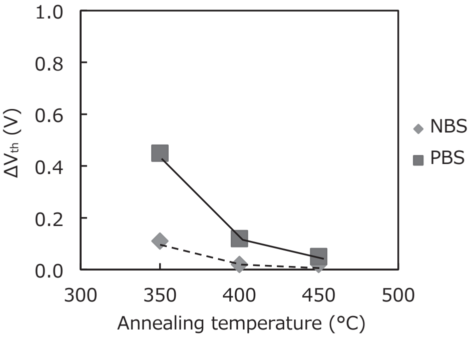

Fig. 7. Annealing temperature dependence of stability (Passivation layer: PECVD-SiO_2)

4. Conclusion

The newly developed In-W-Zn-O sputtering target offers high sintered density and low electrical resistivity comparable to the conventional sintered material of the IGZO sputtering target. Using the In-W-Zn-O sputtering target, we fabricated a TFT and evaluated it. The evaluation revealed electron mobility more than three times better than that of IGZO, and stability, an important characteristic for practical applications, higher than that of IGZO. Compared with IGZO, In-W-Zn-O does not decrease in mobility even with the use of a higher annealing temperature. Consequently, the newly developed material offers improved stability.

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Technical Terms

∗1	Thin film transistor (TFT): A kind of field effect transistor, typically consisting of three terminals: source, drain, and gate. A TFT is comprised of thin films ranging from tens of nm to hundreds of nm including the channel layer.
∗2	From FHD to 4K and 8K: FPD screen resolutions. The numbers of pixels are 1920 (H) × 1080 (V) for full high definition (FHD), 3840 (H) × 2160 (V) for 4K, and 7680 (H) × 4320 (V) for 8K, with the pixel size decreasing in this order if the screen size is the same.
∗3	Electron mobility: The rate of electrons moving through a semiconductor. This paper discusses the field-effect mobility determined from changes in I_{ds} observed in response to changes in V_{gs} with V_{ds} maintained constant at 0.1 V.
∗4	a-Si: Amorphous silicon. a-Si is most widely used in FPDs.
∗5	LTPS: Low-temperature poly-silicon (LTPS) consists of fine silicon crystals approximately 0.3 μm in size. LTPS is manufactured at a low crystallization temperature. The material is said to be difficult to use on glass substrates larger than G6 size due to the issue of uniformity of the laser used for crystallization.
∗6	Sputtering: A film deposition process in which argon ions collide with a solid material biased with a negative voltage under reduced pressure to eject atoms of the solid material for deposition onto an opposed substrate. Sputtering involving the application of a DC voltage to a solid material is known as DC sputtering.
∗7	Stability test (NBS/PBS): In this paper, stability tests refer to negative bias stress (NBS) and positive bias stress (PBS) tests. A negative or positive voltage is continuously applied across the source and the gate. Transfer characteristics are measured at fixed intervals to determine the magnitude of shift in V_{th}. Smaller shifts are indicative of higher stability.

＊8 V_{th}: Threshold voltage. In this paper, the threshold voltage is defined as the intersection point between the x-axis and the steepest-slope tangent line to the curve that represents the gate voltage plotted on the x-axis and the square root of the drain current $[(I_{ds})^{1/2}]$ plotted on the y-axis. A V_{th} value close to 1 V, as with a-Si, is highly usable with FPDs.

＊9 Sub-threshold swing (SS) value: A gate voltage increment required to increase the drain current by an order of magnitude where changes in the gate voltage cause the drain current to change the most. Smaller SS values are better.

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