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Activation and Defect Reduction of Hydrogenated In–Ga–Zn–O Thin Film Transistor at Low Temperature (150 °C)

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Abstract

Herein is a proposed technique to activate sputtered-In–Ga–Zn–O for thin-film transistor (IGZO TFT) at a low temperature (150 °C) by introducing hydrogen as an additive gas alongside oxygen and argon during sputtering. Compared with the Ar+O_2-sputtered IGZO TFTs with a process temperature of 300 °C, the Ar+O_2+H_2-sputtered TFTs exhibited superior electrical characteristics despite a processing temperature of 150 °C. This process is also effective to reduce the defect sites in the IGZO films at a low temperature annealing.

1. Introduction

In–Ga–Zn–O (IGZO) thin-film transistors (TFTs) have received considerable attention for use in next-generation active-matrix displays because they exhibit higher electron mobility (μ_{FE} >10 $cm^2V^{-1}s^{-1}$) as compared with conventional amorphous Si TFTs.[1] Although an IGZO film can be deposited by sputtering at room temperature, the defect sites can be generated in IGZO films during the sputtering process by high-energy target ions and recoil argon. Therefore, a subsequent annealing temperature of 300 °C or higher is required to recover those defects.[2] To improve the TFT characteristics and reliability, this required post-annealing is often called "activation annealing". The processing temperature of the TFTs must be reduced to a level below the transition temperature of a plastic substrate, which is usually around 150 °C for inexpensive commercial flexible substrates such as Polyethylene naphthalate (PEN). Hence, it would be highly desirable to reduce the annealing temperature in order to use an IGZO active channel in flexible electronic applications. Several activation methods for oxide semiconductors have been proposed to reduce the annealing temperature, such as wet O_2 annealing, simultaneous ultraviolet and thermal treatment, high-pressure gas annealing, and electric-field-aided activation [3]. In contrast, a low temperature activation process using additive gas during sputter would be more beneficial as it will reduce production costs. Furthermore, reduction of the bulk defect sites would lead to highly reliable IGZO TFTs.

In this report, we demonstrated that adding a hydrogen gas during IGZO sputtering can help to activate the IGZO films and help to reduce the defect sites at a maximum processing temperature of 150 °C. To investigate this procedure, the TFTs were fabricated using Ar+O_2+H_2-sputtered IGZO, namely, hydrogenated IGZO TFT and the results were compared to conventional Ar+O_2-sputtered IGZO TFTs using various annealing temperatures. The electrical properties of the hydrogenated IGZO TFTs were markedly improved as compared with those of conventional Ar+O_2-sputtered IGZO TFTs at an annealing temperature of 150 °C. Furthermore, the carrier density of the IGZO films were able to controlled by varying the H_2 amounts during sputtering.

2. Experimental

An inverted–staggered bottom gate IGZO TFT was fabricated on a heavily-doped p-type Si which also acts as the gate electrode. The 100-nm-thick thermally grown SiO_2 served as the gate insulator. The IGZO films were deposited by a DC-magnetron sputtering from a ceramic $InGaZnO_4$ (atomic ratio of In: Ga: Zn = 1: 1: 1) target at room temperature. The O_2 and H_2 gas ratios were defined as $R(O_2) = O_2/(Ar+O_2+H_2)$ and $R(H_2) = H_2/(Ar+O_2+H_2)$, respectively. The source/drain (S/D) electrodes were also deposited by sputtering. Both the channel and S/D were patterned by shadow masking. Finally, the TFTs were subjected to annealing in air at 150 to 350 °C for 1 h. The channel length (L) and width (W) were 350 and 1400 μm, respectively.

3. Result and Discussion

Figure 1 (a) shows the transfer characteristics of the TFT with a conventional Ar+O_2-sputtered IGZO channel using an $R(O_2)$ of 1%, as a function of the annealing temperature (T_a). The TFTs changed from conductor to semiconductor at a T_a of 300 °C. This result indicates that, at least a 300 °C activation annealing process should be applied to obtain proper electrical characteristics. In contrast, the TFT with Ar+O_2+H_2-sputtered IGZO channel exhibited excellent electrical properties at T_a of 150 °C, as shown in Fig. 1(b). The turn on voltage (V_{on}) shifted positively by increasing the $R(H_2)$, indicating that the carrier density can be controlled by the hydrogen amount even at a low temperature (T_a of 150 °C). Table I summarizes the electrical properties of those activated TFTs shown in Fig. 1(a) and (b).

In general, the carrier density of the IGZO films can be controlled by varying the oxygen amount during sputtering, as the oxygen deficiencies decrease with an increase in the oxygen concentration. Figure 1(c) shows the TFT properties with the Ar+O_2-sputtered IGZO channel obtained using $R(O_2)$ values from 1 to 5 % after annealing at 150 °C. For $R(O_2)$ values

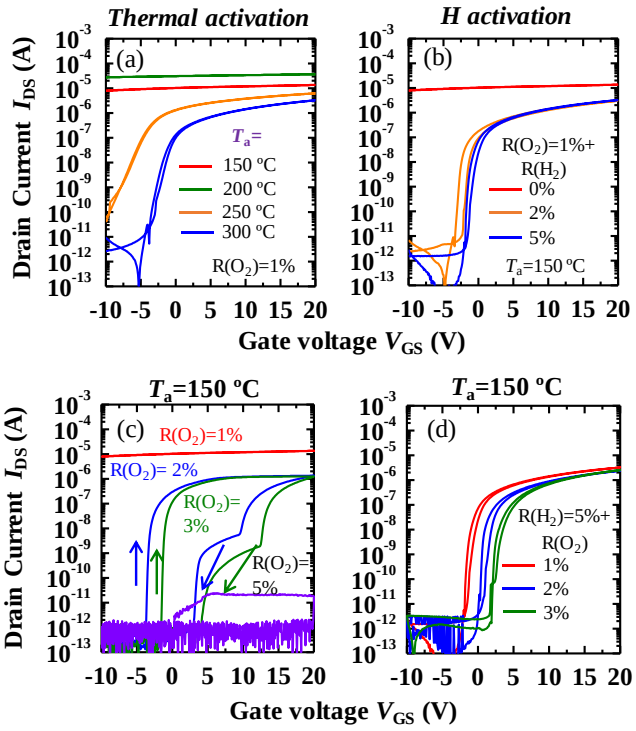

Fig. 1 Transfer characteristics of IGZO TFTs with (a) Thermal and (b) Hydrogenated activated (at 150 °C) IGZO TFTs as a function of annealing temperature and R(H_2), respectively. After annealing at 150 °C with (c) various R(O_2) values and (d) [R(H2) = 5%] + various R(O_2). All of the measurements were performed at V_{DS} = 0.1V, with a double sweeping V_{GS} mode.

Table I Summary of the electrical properties IGZO TFTs shown in Fig. 1(a) and (b).

R(O_2) = 1% + R(H_2)	T_a (°C)	μ_{FE} (cm^2/Vs)	*S.S.* (V/dec.)	V_{on} (V)	Hysteresis (V)
0%	300	14.5	0.35	-2.65	0.6
2%	150	12.1	0.26	-2.80	1
5%	150	13.4	0.13	-1.49	0.6

of 1 and 5 %, the TFTs showed conductor and insulator behavior, respectively. For R(O_2) with a value of 2%, the TFT showed switching properties with a huge hysteresis and hump. Although, the V_{on} moves forward, the huge hysteresis of approximately 7V was not improved by increasing the R(O_2) value to 3%. Therefore, the defects in the subgap states cannot be reduced with conventional sputtering methods at a maximum processing temperature of 150 °C. In contrast, the transfer characteristics of the hydrogenated TFTs show good electrical properties as shown in Fig. 1(d). Those TFTs were fabricated using the IGZO channel with a R(H_2) of 5% and different values of R(O_2), which were varied from 1% to 3%. Despite the $V_{on,}$ other characteristic parameters are mostly identical with a subthreshold swing (*S.S.*) of 0.2 v/dec. and a mobility (μ_{FE}) of 13 cm^2V^{-1} s^{-1}). The positive shift of V_{on} with respect to R(O_2) is commonly observed in most of the AOS-TFT after activation.

The obtained results can interpreted like that, because of the lack of metal-oxide (M-O) bonds after deposition, IGZO films suffer from structural defects. A thermal annealing of 300 °C or higher is required to achieve strong chemical bonding and to reduce the defect sites. In contrast, TFTs with hydrogenated IGZO channels exhibit superior electrical properties, indicates the defect sites were reduced after low temperature (150 °C) annealing. One plausible explanation for the defect reduction is that hydrogen anion (H^-) which substitutes the oxygen vacancy as the ionic radii of H^- is similar to that of oxygen vacancy. Another plausible explanation is increasing the R(H_2) during sputtering results in a reducing atmosphere. The hydrogen would reduce weakly bonded O and/ or –OH and preferentially binds to the undercoordinated oxygen atom and compensates for electron deficit. Thermal desorption spectroscopy (TDS) and X-ray photoelectron spectroscopy (XPS) also revealed that a greater concentration of –OH bonds were present in the Ar+O_2+H_2-sputtered film (data not shown here) [3].

3. Conclusions

We have investigated the electrical properties of Ar+O_2+H_2-sputtered IGZO films for low-temperature processed IGZO TFTs. The electrical properties of the hydrogenated IGZO TFT were markedly improved at low temperature annealing due to the subgap defect reduction. The proposed method can easily be implemented without any extra costs, hence we believe this technique is very promising not only for next-generation display applications but also for the future of flexible electronics.

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