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Improvement of Device Characteristic on Solution-Processed InGaZnO Thin-Film-Transistor (TFTs) using Microwave Irradiation

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***Abstract*—Solution-derived amorphous indium-gallium-zinc oxide (*a*-IGZO) thin-film-transistor (TFTs) were developed using a microwave irradiation treatment at low process temperature below 300°C. Compared to conventional furnace-annealing, the *a*-IGZO TFTs annealed by microwave irradiation exhibited better electrical characteristics in terms of field effect mobility, SS, and on/off current ratio, although the annealing temperature of microwave irradiation is much lower than that of furnace annealing. The microwave irradiated TFTs showed a smaller V_{th} shift under the positive gate bias stress (PGBS) and negative gate bias stress (NGBS) tests owing to a lower ratio of oxygen vacancies, surface absorbed oxygen molecules, and reduced interface trapping in *a*-IGZO. Therefore, microwave irradiation is very promising to low-temperature process.**

***Index Terms*—a-IGZO TFT, solution process, microwave irradiation, low thermal process**

I. INTRODUCTION

Recently, technologies for the realization of a display with a fast response speed, large area, and high resolution have been actively investigated. In order to realize these technologies, most flat panel displays have been fabricated using an active driving method. Thin-film-transistors (TFTs) are mainly used as a switching device for operating the display [1]. To date, for the materials of the channel that is used for the TFT backplane of the active driving display, hydrogenated amorphous silicon (*a*-Si:H) and poly-Si are typical [2]. Hydrogenated amorphous silicon is used primarily in the manufacture of TFT-LCD. The manufacturing process is relatively simple and, stable. Also, the production costs are low and the device characteristics are uniform, which is advantageous for the production of large area displays. However, silicon-based transistors have several drawbacks. *a*-Si:H TFTs have low mobility below 1cm^2/Vs. The development of displays that require a large area, high-definition, and high-speed operation is reaching the limit. As an alternative and as a way to overcome the problems of the silicon-based transistors, amorphous oxide semiconductors (AOSs) have recently received considerable attention. Among these AOSs, amorphous indium-gallium-zinc oxide (*a*-IGZO) TFTs is considered one of the most promising materials for backplane electronic devices of next-generation display applications because of their outstanding electrical properties such as high mobility, excellent on/off ratio even in the amorphous phase, and fully transparent [3]. However, oxide TFTs require manufactured vacuum deposition based technologies, such as chemical vapor deposition (CVD) and radio frequency (RF) magnetron sputter. The vacuum deposition method is time consuming and expensive, and large areas are limited [4]. Also, despite their superior electrical characteristics, *a*-IGZO TFTs have a shortcoming whereby the operating

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threshold voltage of the device is unstable. To overcome these disadvantages, conventional thermal furnace annealing is mainly used as a countermeasure. However, conventional thermal furnace annealing by heat transfer indirect method has drawbacks, including low energy transfer efficiency, high cost, and is a time-consuming process. Also, the solution deposited *a*-IGZO active layer typically requires a high temperature annealing process [5-7]. The conventional annealing methods are limited due to low efficiency of heating and a high thermal process. Also, applying a flexible substrate or a glass substrate high-temperature heat treatment is impossible. Recently, to overcome these problems, various low-temperature annealing techniques have been reported: infra-red annealing [8], ultraviolet photo-annealing [9], and high pressure annealing [10]. In this work, we fabricated the solution deposited *a*-IGZO TFTs at a low temperature using microwave irradiation, which can be applied to the diverse substrates due to its low heating process, as a solution to this problem. The microwave irradiation process has many advantages of unexpected species diffusion, such as rapid annealing process, thermal uniformity, and suppression of unexpected species diffusion. Also, the microwave irradiation process has high energy efficiency of heating and low thermal budget, because the microwave irradiation process can directly transfer the thermal energy to the target materials by absorbing the energy throughout the volume of the material. Therefore, we conclude that the microwave irradiation process effectively removes the defects in *a*-IGZO channel and improves the gate insulator/channel interfaces at low temperature. Besides, the microwave irradiation process showed a feasibility for industrialization for the above reason.

II. EXPERIMENT

The TFT device was fabricated on a p-type (100) Si wafer with a resistivity of 10 Ω·cm. The precursor for the InGaZnO solution was synthesized using a sol-gel reaction. Indium nitrate hydrate [$In(NO_3)_3 \cdot xH_2O$], gallium nitrate hydrate [$Ga(NO_3)_3 \cdot xH_2O$], and zinc acetate dehydrate [$Zn(CH_3COO)_2 \cdot xH_2O$] were used as precursors. These were dissolved in 2-methoxyethanol [$C_3H_8O_2$], and we used the mono-ethanolamine [O_2H_7NO] in order to improve the stability of coating. The stock solution was stirred for 2 hours at 50 ^oC and was then filtered through a 0.2 um syringe filter. The *a*-IGZO thin films were deposited on 100 nm thick SiO_2/Si by the spin-coating method. The *a*-IGZO precursor solution was spin-coated at 6000 rpm for 30 sec in air. After spin coating, the solution *a*-IGZO was baked at 180^{o}C for 10 min in air to remove residual solvent. The active regions of the TFTs were patterned using photo-lithography and etched using a 30:1 buffered oxide etchant (BOE).The defined channel length (L) and width (W) of *a*-IGZO TFTs were 20 μm and 10 μm, respectively. To improve the electrical properties of *a*-IGZO TFTs, a post-deposition annealing (PDA) process was carried out using two annealing methods: conventional furnace thermal annealing and microwave irradiation. Here, the furnace annealing was conducted at 500°C for 30 min under nitrogen (N_2) ambient, and the microwave irradiation was performed at 200, 250, and 300°C for 20 min in air, Subsequently, the source/drain electrodes (Ti/Au=10/100 nm) were formed using e-beam evaporation. Finally, for the formation of the gate electrode, aluminum (Al) with a thickness of 150 nm was deposited using an e-beam evaporator. The schematic representation of the fabricated *a*-IGZO TFTs with a back-gate structure is shown in Fig. 1. The electrical properties of the *a*-IGZO TFTs were characterized using a semiconductor parameter analyzer (HP 4156B) in a dark box at room temperature. The instability of devices was evaluated from the threshold voltage shift under the positive/negative gate bias (PBS/NBS) stress (V_{GS} = ±20 V, V_{DS} = 10 V) for 1 hour. In addition, X-ray photoelectron spectroscopy (XPS) measurements were

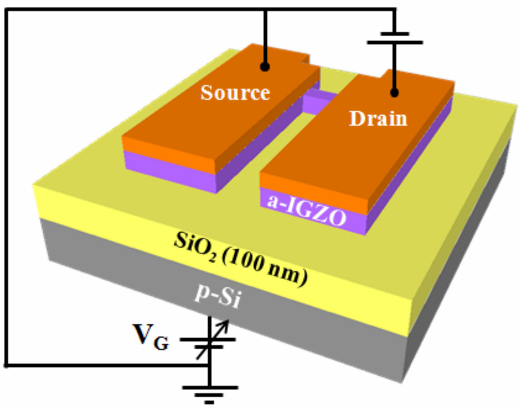

Fig. 1. Schematic representation of *a*-IGZO TFTs with back-gate structure.

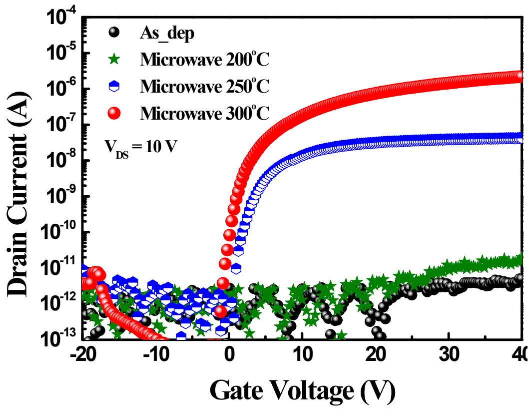

Fig. 2. Transfer characteristic curves (I_D-V_G) of *a*-IGZO TFTs annealed using microwave irradiation at 200, 250, and 300°C.

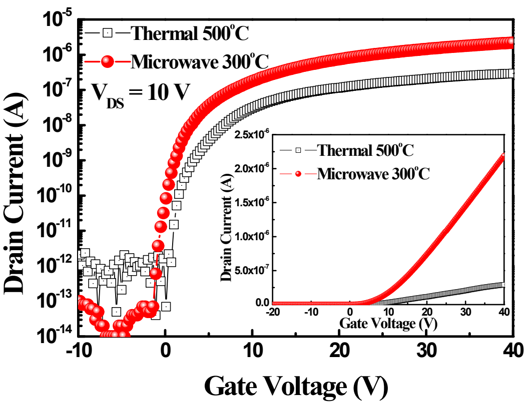

Fig. 3. Transfer characteristic curves (I_D-V_G) of *a*-IGZO TFTs annealed in a conventional furnace at 500°C and microwave irradiation at 300°C.

performed to analyze the types of chemical bonds of the IGZO films.

III. RESULTS AND DISCUSSION

Fig. 2 shows the transfer characteristic curves (I_D-V_G) of *a*-IGZO TFTs annealed by microwave irradiation at 200°C, 250°C, and 300°C. It is found that low temperature annealing below 200°C cannot improve the performance of devices because the channel was not formed in the *a*-IGZO layer. This is because the *a*-IGZO TFTs channel is not subjected to sufficient energy for chemical bonding and a large number of defects remain in the channel region. However, this problem can be solved by using an annealing temperature higher than 200°C, leading to improved device performance. The electrical parameters of the fabricated *a*-IGZO TFTs are summarized in Table 1. Also, the results, obtained in previous work by using low-temperature processes such as Infra-red annealing, ultraviolet photo-annealing, and high pressure annealing for the solution processed *a*-IGZO TFTs, are summarized. The *a*-IGZO TFTs annealed at 250°C show the transfer curves of the field-effect transistors with a low operation current. The devices annealed at 300°C by using microwave irradiation showed a high field-effect mobility of 3.82 $cm^2/V\cdot s$, a good subthreshold swing (SS) of 317 mV/dec, and an excellent on/off current ratio of 3.13×10^7.

Fig. 3 shows the transfer characteristic curves (I_D-V_G) of *a*-IGZO TFTs annealed by conventional furnace and microwave irradiation at 500°C and 300°C. Compared to the conventional furnace-annealed devices, the *a*-IGZO TFTs annealed by microwave irradiation exhibited better electrical characteristic in terms of field effect mobility, SS, and on/off current ratio, although the annealing temperature of the microwave irradiation process was much lower than that of furnace annealing. This is because the microwave irradiation process enhanced the bonding of the oxygen ions and effectively eliminated the defects in the channel layer [11, 12].

Table 1. Comparison of the performances of the low temperature solution-processed IGZO TFTs in previous works

Annealing method	Materials	Annealing temperature (°C)	Mobility [$cm^2/V\cdot s$]	On/Off Current ratio	S.S. [mV/dec]
Microwave (this paper)	IGZO	200°C 250°C 300°C	N/A 0.12 3.82	N/A 1.03×10^6 3.13×10^7	N/A 407 318
conventional (this paper)	IGZO	300°C	0.8	2.27×10^6	337
High-pressure [8]	IGZO	220°C 250°C	1.81 3.13	6.5×10^6 8.0×10^6	630 690
conventional [9]	IGZO	250°C 300°C	0.05 0.2	1.0×10^5 5.0×10^5	N/A N/A
Infrared [10]	IGZO	300°C	2.04	1.5×10^6	840

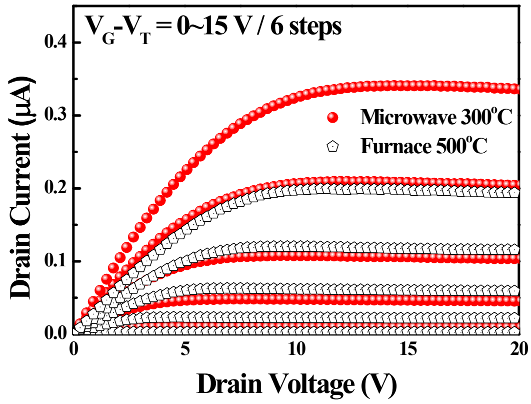

Fig. 4. Output characteristic curves (I_D-V_D) of *a*-IGZO TFTs annealed in a conventional furnace at 500°C and microwave irradiation at 300°C.

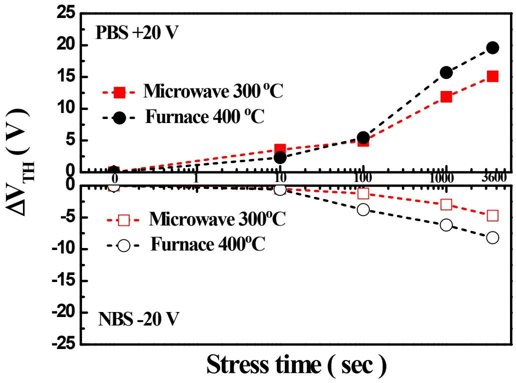

Fig. 5. Threshold voltage shift of *a*-IGZO TFTs annealed using microwave at 300°C and furnace at 400°C as a function of PGBS/NGBS time.

Fig. 4 shows the typical output characteristic curves (I_D-V_D) of *a*-IGZO TFTs annealed by microwave irradiation and conventional furnace at 300°C and 500°C. The drain current (I_D) increased abruptly as the drain voltage (V_D) increased at a positive gate bias (V_{GS}), indicating the generation of electron carriers. Moreover, the output characteristics showed a clear pinch-off and drain current saturation. The saturation current of *a*-IGZO TFTs annealed by microwave irradiation at 300°C is higher than that annealed by conventional furnace at 500°C.

One of the most important issues in *a*-GIZO TFTs is reliability. Positive gate bias stress (PGBS) and negative gate bias stress (NGBS) tests were carried out to examine the device reliability, as shown in Fig. 5. The initial V_{th} is shifted to positive or negative voltage directions according to the polarity of the applied gate bias. It can be seen that ΔV_{th} increased with stress time. The V_{th} shift by PGBS is mainly ascribed to the influence of absorbed oxygen molecules reacting on the surface, which can be expressed in the form of O_2 (gas) + e^- → $2O^-$ (solid) [13]. When a positive gate bias was applied to the *a*-IGZO film, the conduction electrons (e^-) were extracted by the surrounding oxygen molecules, resulting in increased negatively charged oxygen (O_2^-) adsorption on the surface. The depletion layer then expanded and the channel potential increased, leading to an increase of V_{th}. The microwave irradiated TFT showed a smaller V_{th} shift owing to the reduced surface oxygen adsorption and charge trapping at the dielectric/*a*-IGZO channel layer, thus improving the electrical stability after PGBS. On the other hand, a negative shift of V_{th} with increasing negative bias stressing time is attributed to the film defects, interface charge traps, and neutral oxygen vacancies serving as electron donors.

Fig. 6 shows the O 1s peaks of XPS measured to analyze the types of chemical bonds between metal atoms (In, Zn, Ga) and O atom after (a) conventional furnace annealing and (b) microwave irradiation. The O 1s peaks can be fitted using two Gaussian curves centered at 530 and 531 eV, respectively. The peak at the lower binding energy of 530 eV (O_I) is attributed to the O^- ions present in the stoichiometric IGZO structure. The peak with the higher binding energy of 531 eV (O_{II}) is typically associated with the presence of oxygen-deficient regions or loosely bound oxygen on the surface, attributed to H_2O and OH groups incorporated into the materials [13,14]. The ratio of the peak area $O_{II}/O_I + O_{II}$, which indicates the relative quantity of the oxygen-related defects, decreased from 32.1% (for conventional furnace annealing) to 27.6% (for microwave irradiation). The lower ratio of oxygen vacancies and surface absorbed oxygen molecules is related to charge trapping and increases the electrical stability of TFT devices. As shown in Fig. 5, the microwave irradiated TFT showed only a small V_{th} shift due to the reduced oxygen vacancies and interface trapping in *a*-IGZO, thus improving the electrical stability after NGBS. These results show that the microwave irradiation can effectively improve the immunity of PGBS and NGBS by eliminating the defects in the *a*-IGZO channel and improving the gate insulator/channel interfaces. Thus, the

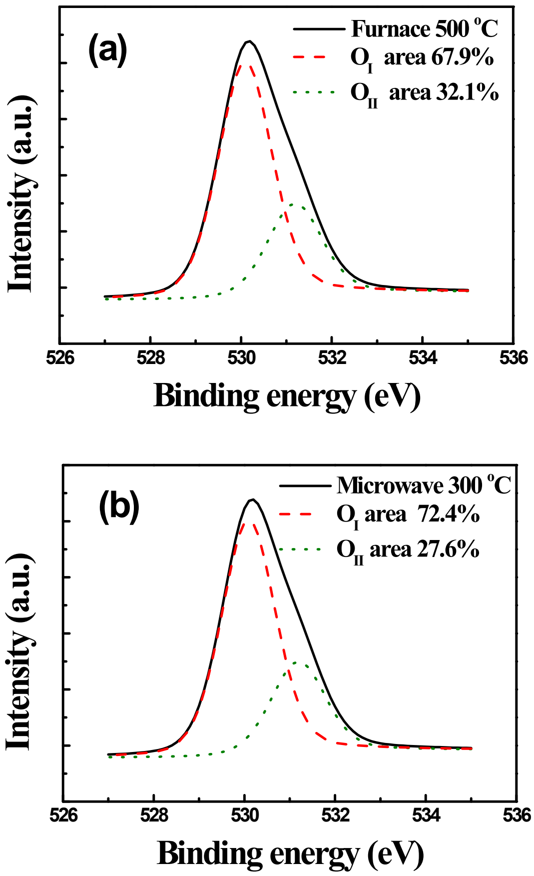

Fig. 6. O 1s peaks of XPS for (a) conventional furnace annealing, (b) microwave irradiation.

microwave irradiation is very promising for low-temperature processes.

IV. CONCLUSIONS

In this study, we developed solution-derived amorphous indium-gallium-zinc oxide (*a*-IGZO) thin-film-transistors (TFTs) using microwave irradiation at low process temperature below 300°C. Compared to the conventional furnace-annealing, the *a*-IGZO TFTs annealed by microwave irradiation exhibited better electrical characteristics: high field-effect-mobility of 3.82 cm^2 V^{-1}s^{-1}, high on/off current ratio of 3×10^7, and small subthreshold swing of 317 mV/dec, even though the annealing temperature of the microwave irradiation is much lower than that of furnace annealing. Furthermore, the microwave irradiated TFT showed a smaller V$_{th}$ shift under positive gate bias stress (PGBS) and negative gate bias stress (NGBS) tests owing to the lower ratio of oxygen vacancies, surface absorbed oxygen molecules, and reduced interface trapping in *a*-IGZO.

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