K-8-03 Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp739-740

Microwave-assisted Calcination of IGZO Nanofibers Field-effect Transistors for Transparent and Flexible Electronic Devices

Hyeong Un Jeon, and Won-Ju Cho*

Department of Electronic Materials Engineering, Kwangwoon University, Seoul 139-701, Republic of Korea
Phone: +82-2-940-5163 *E-mail: chowj@kw.ac.kr

Abstract

In this study, we calcined the electrospun In-Ga-Zn-O (IGZO) nanofibers through microwave irradiation with a low thermal budget. Then, high-performance field-effect transistors (FETs) were fabricated using microwave-assisted calcined nanofibers. In parallel, the IGZO nanofibers were calcined by conventional thermal annealing (CTA), and then FETs were fabricated to compare electrical characteristics. In addition, we constructed resistor-loaded inverters using microwave-assisted or CTA calcined FETs to evaluate static and dynamic behavior under DC and pulse stress conditions. As a result, the electrical properties of the nanofiber FETs were significantly improved by microwave-assisted calcination compared to CTA calcination. In addition, microwave-assisted calcination FETs showed better stability than CTA calcination devices through positive or negative gate bias temperature stress. Meanwhile, resistor-loaded inverters constructed with microwave-calcined nanofiber FETs exhibited better static and dynamic behavior than those constructed with CTA calcined FETs. Consequently, we believe that microwave-assisted calcination is capable of fabricating high-performance IGZO nanofiber FETs with a low thermal budget and is effective in implementing transparent and flexible electronic devices.

1. Introduction

Recently, with the development of next-generation display backplane thin-film transistors (TFTs), new materials with high transparency, flexibility, and ease to form large-area are required. From this point of view, the nanofibers, not existing thin-film structure has no limitations of flexibility, transparency, and large area process. In particular, electrospinning technology can easily form metal oxide nanofibers, such as In-Ga-Zn-O (IGZO). Electrospinning technology can achieve various advantages such as adjusting the composition ratio and no need for a vacuum. However, the presence of the polymer matrix in electrospun nanofibers can lead to defects in metal oxides, which can adversely affect the electrical characteristics of devices and circuit implementations. Therefore, many studies have been conducted such as calcination annealing to improve this problem. [1] Adequate calcination process can maximize the characteristics of electrospun IGZO nanofibers. Among them, there is a low thermal budget microwave annealing (MWA) using electromagnetic waves as calcination annealing. MWA is a highly efficient annealing method that can transfer uniform heat energy to the device using the rotation of dipole in materials by an electromagnetic wave. [2] On the other hand, conventional thermal annealing (CTA) has a high thermal budget and it can exert a degradation on element properties by applying fatal stress to materials such as flexible substrates, or biocompatible polymers. In other words, stabilization of device characteristics and substrate constraints are trade-off in CTA calcined field-effect transistors (FETs). Despite these disadvantages, most of the devices used CTA to calcination. In contrast, few studies about using MWA calcined devices have reported. Thus, in this study, we formed IGZO nanofibers using electrospinning technology and fabricated FETs through microwave-assisted calcination process. Also, in order to confirm the effect of MWA, the electrical performance of the devices treated with CTA and MWA was evaluated. As a result, although the MWA-treated device had a shorter annealing time than the CTA-treated device, the performance was improved. In addition, MWA dramatically improves the inverter operation of IGZO nanofibers FETs based resister-loaded inverter. Furthermore, instability evaluation using positive bias temperature stress (PBTS) and negative bias temperature stress (NBTS) test showed that MWA improves the stability of IGZO nanofibers FETs. Therefore, the MWA calcination process is expected to be a useful technique for fabricating high-performance IGZO nanofibers FETs with a low thermal budget process and can be applied to flexible display fields or limited substrate in high temperature.

2. General Instructions

A 10 Ω·cm (100)-oriented p-type Si wafer was cleaned by a standard RCA (Radio Corporation of America) process, and then a 100-nm-thick SiO_2 layer for a gate insulator was grown through thermal oxidation. As a channel layer of FETs, IGZO nanofibers were electrospun using an IGZO precursor solution. For improvement of mechanical and electrical properties of electrospun nanofibers, solvent and residual polymers were removed by microwave-assisted calcination at 1800 W for 5 minutes in air ambient using microwave furnace. For comparison, the control (CTA) group was calcined at 600 °C in O_2 ambient for 30 minutes using a thermal processing furnace. Then, the active region was defined by photolithography and wet-etching technique using a 30:1 ratio of buffer oxide etchant (BOE). Finally, IGZO nanofiber FETs were fabricated by depositing a 150 nm-thick Ti layer using e-beam evaporator, and forming the source and drain electrodes through the lift-off process. The width and length of the nanofiber channels are 10 μm and 20 μm, respectively.

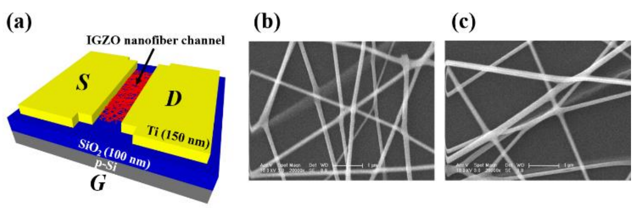

Fig. 1 (a) Schematic diagram of IGZO nanofibers FETs. SEM images (×20,000) of (b) MWA- and (c) CTA-calcined IGZO nanofiber

The schematic diagram of the fabricated FETs is shown in Fig. 1(a). The scanning electron microscope (SEM) images of the IGZO nanofiber calcined by MWA or CTA are shown in Figs. 1(b) and (c), respectively.

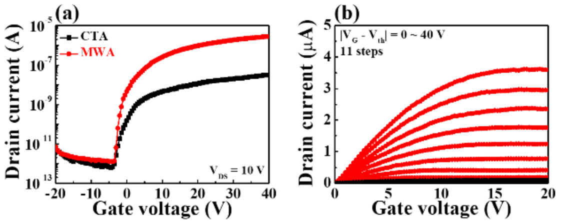

Fig. 2 (a) Transfer and (b) output characteristic curves of MWA-assisted or CTA-calcined IGZO nanofibers FETs.

Fig. 2(a) and (b) show transfer (I_D-V_G) and output characteristic curves (I_D-V_D) of MWA-assisted or CTA-calcined nanofibers FETs. It can be seen that MWA-calcined nanofibers have better electrical characteristics than CTA-calcined nanofibers despite shorter process times.

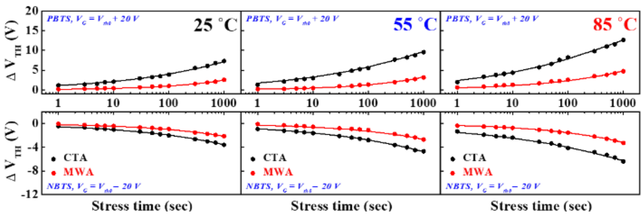

Fig. 3 Threshold voltage change (ΔV_{th}) under the positive and negative gate bias until 10^3 seconds at 25, 55, and 85 °C of MWA- and CTA- calcined IGZO nanofibers FETs.

Fig. 3 shows the threshold voltage change (ΔV_{th}) of IGZO nanofiber FETs measured for 10^3 seconds using PBTS ($V_G = V_{th0} + 20$ V) and NBTS ($V_G = V_{th0} - 20$ V) tests at 25, 55 and 85 °C, respectively, where V_{th0} is the initial V_{th} of the unstressed device. ΔV_{th} increases with the stress time and temperature, the increase rate is dependent on the stress temperature. It is noteworthy that the ΔV_{th} of the MWA-calcined device is smaller than the CTA-calcined one.

Table 1. τ and E_τ under PBTS and NBTS tests of MWA- and CTA-calcined IGZO nanofibers FETs

Calcination method		Charge trapping time, τ [sec]			Energy Barrier, E_τ [eV]
		25 °C	55 °C	85 °C	
CTA	PBTS	1.5×10^4	4.0×10^4	1.0×10^3	0.42
	NBTS	5.0×10^5	3.2×10^5	1.8×10^5	0.23
MWA	PBTS	1.1×10^5	5.0×10^4	2.0×10^4	0.26
	NBTS	3.0×10^5	1.5×10^5	6.8×10^4	0.16

Table. 1 summarizes the charge trapping time (τ) extracted from Fig. 3 and the effective energy barrier (Eτ) extracted from the Arrhenius relationship between the ln (τ) and 1/T. MWA-calcined nanofiber FET has a higher τ than CTA-calcined device, which means that MWA-calcined device capture charge more slowly than CTA-calcined devices, improving long-term stability. Moreover, the E_τ of the MWA-calcined device is lower than that of the CTA-calcined device, which means a nanofibers channel with lower defect density and better lattice arrangement, improving device instability.

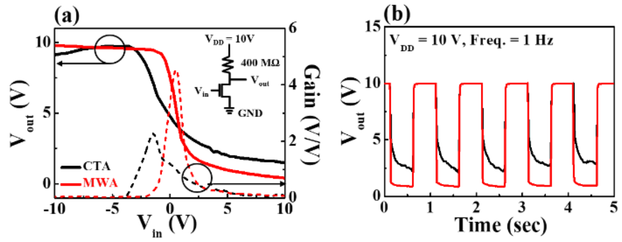

Fig. 4 (a) Voltage transfer characteristic. Inset is the equivalent circuit diagram of resistor-loaded inverter based on IGZO nanofiber FETs. (b) Dynamic inverting response at 1 Hz.

Fig. 4 shows the resister-loaded inverter characteristics constructed using an IGZO nanofiber FET and a resistor. Fig. 4(a) is the voltage transfer characteristics (VTC) indicating the static behavior of the inverter. As the input voltage (V_{in}) sweeps from -10 V ("0" state) to 10 V ("1" state), the output voltage (V_{out}) changes from 10 V ("1" state) to 0 V ("0" state). It can be seen that the MWA-calcined device has better inverter switching characteristics and gain (dashed line) than the CTA calcined device. Fig. 4(b) is the dynamic behavior under pulsed stress conditions of 1 Hz. The MWA-calcined device shows a stable inverter operation. However, in parallel to the VTC degradation, the overall speed of the CTA-calcined device declines, as the increased delay time shows. We attribute this behavior to the build-up of the charge trap as the increased V_{th} shows in Fig. 3. Therefore, the MWA-assisted calcination is more effective than CTA calcination to improve the performance and instability of IGZO nanofiber FETs.

3. Conclusions

In this study, we fabricated high-performance IGZO nanofibers FETs through highly efficient microwave irradiation. We evaluated the improved electrical performance of MWA-calcined devices by transfer curves, output curves, resistor-loaded inverter operation, PBTS, and NBTS test to CTA-calcined device. As a result, MWA-calcined devices exhibited better electrical properties and excellent inverter operation, such as faster switching speed and obvious “1”/"0" state than CTA-calcined device. In addition, MWA-calcined FETs show better stability by a larger τ and an E_τ as well as a smaller ΔV_{th} than the CTA-calcined device. As mentioned previously, MWA-calcined IGZO nanofibers FETs have more advantageous aspect to apply in the display applications by long-term stability. Therefore, we believe that microwave-assisted calcination is a promising technology for implementing transparent, flexible electronic devices through low thermal budget and effective electromagnetic energy transfer.

Acknowledgements

The present Research has been conducted by the Research Grant of Kwangwoon University in 2020. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1A2C1007586).

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