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High-performance 1-dimensional In-Ga-Zn-O Nanofiber Thin Film Transistors on High-*k* Gate Dielectrics by Microwave Irradiation and Oxygen Plasma Treatment

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Abstract

In this study, we fabricated n-type thin film transistors (TFTs) by electrospinning In-Ga-Zn-O (IGZO) nanofibers on various high-*k* gate dielectrics and carried out low thermal budget microwave annealing (MWA) and low temperature oxygen plasma treatment to improve the device characteristics. As a result, the MW-assisted calcination and heat-treatment process more effectively reduced the diameter of nanofibers than conventional furnace annealing (CFA). In particular, the plasma treatment in oxygen ambient considerably enhanced the properties of IGZO nanofiber TFTs. Also, compared to other gate insulators-based TFTs, Ta_2O_5-based TFTs with MWA process exhibited the most excellent electrical properties and showed on-off current ratios of 2.26×10^6, a threshold voltage of 0.43 V, a subthreshold swing of 102.65 mV/dec, and field effect mobility of 0.11 $cm^2/V\cdot s$ for electrons after oxygen plasma treatment. Moreover, the reliability of the TFTs was evaluated by positive bias temperature stress (PBTS) measurement at room temperature and high temperature. SiO_2-based TFTs were the most stable of the devices and oxygen plasma treatment allowed the stability to be improved. Therefore, we expect that low thermal budget MWA technique and oxygen plasma treatment are able to be applied to fabricate high-performanced IGZO nanofiber TFTs used for switching devices of the next generation displays.

1. Introduction

In recent years, as limit of device scaling is challenged, electronics industry is moving toward nanomaterial-enabled electronics such as nanofibers, nanowires, nanoparticles, and nanoribbons [1]. Among them, electrospun 1-dimensional (1 D) semiconducting nanofibers are advantageous in simple process, large area, control of doping concentration, excellent surface-to-volume ratio, and mechanical flexibility [2]. Furthermore, numerous researches that fabricate metal oxide semiconductors with excellent optical transparency and electrical properties in the form of nanofibers and apply them as channel layers of thin film transistors (TFTs) have been reported actively. Meanwhile, various semiconductor fabrication techniques have been adopted for stretchable and transparent electronics application. Among them, microwave-assisted annealing process (MWA) is able to improve the device properties effectively by reducing the fibers diameter and removing the defects in the nanofibers. Particularly, MWA can achieve a low thermal budget process with short annealing duration and low process temperature. Meanwhile, plasma-based surface treatment is environment-friendly technique that enhances the substance properties by modifying the chemical bonds and morphology state at low temperature [3]. Therefore, In this study, we fabricated the TFTs with In-Ga-Zn-O (IGZO) nanofibers as channel layers on various high-*k* gate dielectrics. High efficiency MWA technique and oxygen plasma treatment were used to improve the optical, electrical, and stable property of the IGZO nanofiber TFTs.

2. General Instructions

On the p-type bulk Si wafers, 100-nm-thick of SiO_2 and various high-*k* materials (Al_2O_3, HfO_2, ZrO_2, and Ta_2O_5) were deposited as the bottom gate dielectric by using radio-frequency (RF) magnetron sputtering. Then, the IGZO nanofibers were electrospun as an n-channel layer using an IGZO precursor solution. In order to calcine the IGZO nanofibers and improve the characteristics, MWA at the microwave power of 1800 W in air for 2 minutes and conventional furnace annealing (CFA) at 600 °C in O_2 ambient for 30 minutes, respectively. Then, the IGZO nanofibers were exposed to oxygen plasma at room temperature with the oxygen pressure of 300 mTorr at 200 W for 20 sec. Finally, bottom-gate top-contact type IGZO nanofiber TFTs were fabricated by depositing 150-nm-thick Ti as the source and drain (S/D) electrodes with an E-beam evaporator system by lift-off method.

As shown in Fig. 1, IGZO channel layers were observed in the structure of fibers by scanning electron microscope (SEM) images (×15000). In Fig. 1(a), the average diameters of as-spun IGZO nanofibers were found to be approximately 350 nm. Fig. 1 (b) and (c) show SEM images of 600 °C of CFA- and 1800 W of MWA-treated nanofibers, respectively and both exhibit significantly decreased diameters compared to as-spun nanofibers. Moreover, oxygen plasma treatment resulted in additional reduction of fiber diameters and improvement in fiber uniformity.

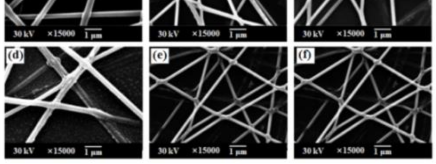

Fig. 1 Scanning electron microscope (SEM) images for (a) as-spun,

(b) CFA 600 ˚C-, (c) MWA 1800 W-treated IGZO nanofibers, respectively and (d) as-spun, (e) CFA 600 ˚C-, (f) MWA 1800 W-treated IGZO nanofibers with oxygen plasma treatment, respectively.

Fig. 2 (a) and (b) show the optical transmittance spectra and the average transmittance in the visible region (wavelenth of 400 – 700 nm) of IGZO nanofibers on glass substrate, respectively. As a result, the lowest average transmittance of 73.6 % was observed in as-spun nanofibers without oxygen plasma treatment and the annealing process largely enhanced the transmittance of IGZO nanofibers. Furthermore, low thermal budget MWA technique was more effective method to increase the optical trasmittance of IGZO nanofibers than CFA. MWA-treated IGZO nanofibers showed the highest transmittance of 93.4 % after oxygen plasma treatment.

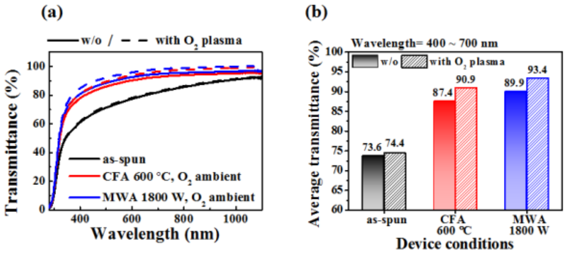

Fig. 2 (a) UV-visible spectra and (b) average transmittance in visible wavelength of IGZO nanofibers on glass substrates before and after annealing process and oxygen plasma treatment.

To evaluate the electrical property of n-type IGZO nanofiber TFTs according to annealing methods and oxygen plasma treatment, I_{DS}-V_{GS} characteristics at the drain voltage (V_D) of 10 V are measured and illustrated in Fig 3. As a result, Ta_2O_5-based TFTs with the highest dielectric constant exhibited the greatest transfer characteristic compare to other gate insulator based-TFTs. Especially, the electrical property of Ta_2O_5-based nanofiber TFTs are maximized by MWA technique and oxygen plasma, indicating on-off current ratios of 2.26×10^6, a threshold voltage of 0.43 V, a subthreshold swing of 102.65 mV/dec, and field effect mobility of 0.11 $cm^2/V\cdot s$ for electrons.

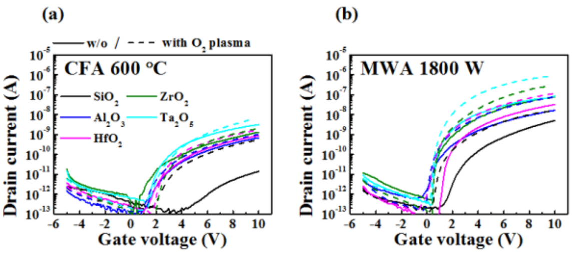

Fig. 3 I_{DS}-V_{GS} characteristics of (a) 600 ˚C of furnace annealed- and (b) 1800 W of MW annealed-IGZO nanofiber TFTs, respectively. The solid line and dash line represent the transfer curves of the TFTs w/o and with oxygen plasma treated, respectively.

Fig. 4 shows threshold shift (ΔV_{TH}) of MW-annealed IGZO nanofiber TFTs under positive gate bias temperature stress at (a) 25 ˚C, (b) 55 ˚C, and (c) 85 ˚C. The devices were exposed to the stress of $V_{GS}= V_{ON0}+5$ V and $V_D= 0$V for 10^3 sec. SiO_2- and ZrO_2-based IGZO nanofiber TFTs exhibited the most stable and unstable property under the gate bias stress, respectively. Also, as the measurement temperature increased, ΔV_{TH} of the TFTs became larger. Oxygen plasma treatment, in particular, influenced on reliability improvement of IGZO nanofiber TFTs.

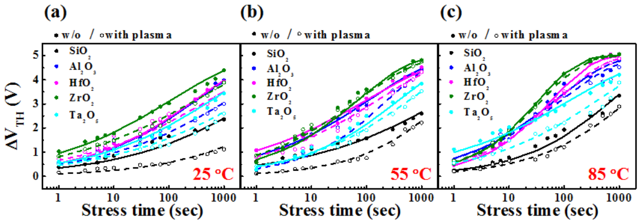

Fig. 4 ΔV_{TH} shift of MW-annealed (1800 W) TFTs along with stress time under positive gate bias temperature stress. We applied a fixed V_{GS} = + 5 V and V_D = 0 V on the TFTs at (a) 25 ˚C, (b) 55 ˚C, and (c) 85 ˚C for 10^3 sec. The fitting curves of w/o and with oxygen plasma-treated IGZO nanofiber TFTs were illustrated by solid line and dash line, respectively.

3. Conclusions

In this study, we fabricated n-type electrospun IGZO nanofiber TFTs on high-*k* gate dielectrics and enhanced the properties through MWA and oxygen plasma treatment. High efficiency MWA technique was more effective in calcining and annealing the IGZO nanofibers than CFA process. Furthermore, plasma treatment in oxygen ambient affects improvement in the morphological, electrical, and reliable characteristics of IGZO nanofibers. Especially, compared to other gate dielectrics, MWA-treated Ta_2O_5-based TFTs showed the greatest electrical property after oxygen plasma treatment. On the other hand, SiO_2-based TFTs indicated the most stable property under PBTS. In conclusion, we propose low thermal budget MWA and low temperature plasma treatment in oxygen for fabricating stretchable and transparent electronics based on IGZO nanofibers.

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