

Effect of UV-assisted low-temperature annealing on electrical performance of Zn-Sn-O nanofiber-based field effect transistors

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ARTICLE INFO

Keywords:

Low-temperature process
Field effect transistor
Ultraviolet
ZnSnO
Nanofibers
Electrospinning

ABSTRACT

Low-temperature fabrication process of thin film transistors is essential for the flexible electronics using plastic substrates. We demonstrated the Zn-Sn-O (ZTO) nanofiber-based field effect transistors (FETs) which were fabricated at low temperature where the plastic substrates can be sustained. The nanofibers (NFs) were prepared by an electrospinning method incorporated with low-temperature decomposable nitrocellulose polymer and ultra-violet (UV) exposure. UV irradiation was applied under varying conditions, and all treated devices exhibited better electrical characteristics than their unirradiated counterparts. The synergetic effect of thermal annealing and photon energy from UV irradiation demonstrated improved adhesion between adjacent nanofibers and the nanofiber/dielectric interface, enhancing the electrical performance of NF-based FETs. The pre-exposure FET (Pre-F) showed the optimal electrical performance with an on/off current ratio exceeding 10^6 , a low threshold voltage of -0.1 V, decent saturation mobility, and density of interface traps of $6.3 \times 10^{12} \text{ cm}^{-2}$. This low-temperature-fabricated ZTO NF-FET can be compatible with flexible polymer substrates, providing a platform for future applications in flexible electronics.

1. Introduction

One-dimensional (1D) nanostructured metal oxide semiconductor (MOS) has widely attracted attention in electronics due to its excellent electrical and mechanical properties [1–3]. MOS NF with 1D nanostructure have been applied in FETs due to their high switching speed with distinctive charge transport characteristics, high integration, and low power consumption [4,5]. In particular, MOS NFs are advantageous for flexible electronics because of their excellent robustness for deformations.

MOS NFs can be fabricated using various methods including electrospinning [6,7], templating [8], solvothermal [9], or self-assembly [10]. Among these, electrospinning is the simplest and lowest cost technology for fabricating well-confined 1D nanostructures [11–13]. Electrospinning is based on stretching of a polymer solution under an applied electric field [14]. In order for NFs to exhibit semiconductor properties, a process of decomposing the polymer through high temperature annealing is essential, but the plastic films cannot withstand the high temperature. This problem has long been a stumbling block for

the applications of NFs to the flexible electronics. Nitrocellulose (NC), one of the polymers used for nanofibers, is known for its environmentally friendly, high elasticity characteristics and low decomposition temperature [15–17]. Due to this, NC is a promising candidate for low-temperature fabrication of flexible electronic devices on plastic substrates.

Another strategy to reduce the annealing temperature is UV irradiation. The UV exposure decomposes organic components in the nanofibers and provides extra energy to induce densification and condensation reaction of composite materials, enabling thermal annealing at lower temperatures [18–23]. Additionally, UV has been reported to enhance the electrical performance of FETs by providing photon energy, inducing generation of carriers, and increasing saturation mobility through the reduction of charge trap sites [24–26]. In nanofiber MOS, UV application can improve adhesion between the nanofiber and dielectric layer [23].

Among the MOSs, indium-based oxides have been extensively studied as active layers in transistors [27,28]. In the literature, indium-oxide (In_2O_3) semiconductors exhibit high electrical performance in FETs due

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<https://doi.org/10.1016/j.mssp.2025.109909>

Received 11 June 2025; Received in revised form 13 July 2025; Accepted 26 July 2025

Available online 30 July 2025

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to their inherent electron mobility [29]. However, indium is a toxic, rare, and expensive material that is unsuitable for future applications requiring eco-friendliness [30,31]. As a promising alternative, zinc-tin oxide has been considered as an active layer in FETs, with a bandgap of 3.6 eV, similar to that of In_2O_3 (3.7 eV) [32]. In addition, Sn is non-toxic, inexpensive, and abundant [30–33]. However, tin-oxide (SnO_2) can induce excessive carriers in the active layer, resulting in poorly controllable device performance [34]. Using Zn as a dopant produces a compensatory role by suppressing the formation of excess carriers [31]. Furthermore, amorphous MOSs have been considered an alternative to high-temperature polycrystalline counterpart owing to their low temperature formation, no grain boundaries, less electron scattering, thereby it can perform more uniform electron transport pathway [35].

In this paper, amorphous ZNFETs were fabricated at a low annealing temperature using NC and UV irradiation. To optimize the device performance, UV irradiation conditions and experimental parameters such as molar ratios of Sn and Zn, nanofiber density, and annealing temperature were adjusted. Two UV wavelengths, 404 and 254 nm, were employed to modulate the electrical tunability in ZNFETs. Specifically, 404 nm UV was applied as a pre-exposure irradiation step before annealing, while 254 nm UV was used for post-exposure irradiation during annealing. The optimal electrical performance was a decent electron mobility of $0.63 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $I_{\text{on}}/I_{\text{off}}$ of 5.84×10^6 , low V_{th} , and small SS. This low-temperature ZNFET is an effective strategy for future interactive electronics.

2. Materials and methods

First, a ZTO precursor solution was prepared by dissolving 0.32 g of tin (IV) chloride pentahydrate, 0.03 g of zinc nitrate, and nitrocellulose (NC) in a co-solvent containing 3 mL of 2-methoxyethanol ($\text{CH}_3\text{OCH}_2\text{CH}_2\text{OH}$, 99.8 %, Merck, South Korea) and 2 mL of acetone (CH_3COCH_3 , 99.5 %, DAEJUNG). 2-Methoxyethanol was used as the main solvent to completely dissolve tin chloride pentahydrate and zinc nitrate, and acetone was used as the auxiliary solvent to completely dissolve NC. The total molar concentration was 0.2 M, and Sn:Zn was dissolved in a ratio of 9:1. Nitrocellulose was dissolved at $0.11 \text{ g} \cdot \text{mL}^{-1}$. The solution was stirred at 50°C for more than 12 h.

The ZTO nanofibers were spun on the Si/SiO₂ substrate with dimensions of $2 \text{ cm} \times 2 \text{ cm}$ via the electrospinning process. ZTO nanofibers were ejected by pushing the ZTO solution through a metal needle at a flow rate of $2.0 \text{ mL} \cdot \text{h}^{-1}$, while a DC voltage of 20 kV was applied to the metallic nozzle. The distance between nozzle and Si/SiO₂ substrate was 13 cm. During electrospinning, the drum collector holding the Si/SiO₂ was rotated at 300 rpm. The SiO₂ layer thickness of the Si/SiO₂ substrate was 100 nm, and the layer was cleaned through ultrasonication by acetone and isopropyl alcohol before electrospinning. The electrospinning process was carried out in the ambient relative humidity level $\sim 30 \%$.

In this experiment, two UV irradiation steps were used: pre-exposure and post-exposure. Pre exposure refers to 404 nm UV irradiation with an intensity of $10 \text{ mW} \cdot \text{cm}^{-2}$ for 40 min using a UV exposure system (Model COOLUV – 125) before annealing. Post exposure refers to the process of irradiating with 254 nm UV at an intensity of $0.25 \text{ mW} \cdot \text{cm}^{-2}$ for 3 h using a UV lamp located 10 cm above the sample during annealing. Samples were annealed at 350°C under the different UV irradiation conditions for various annealing times. Afterward, 100 nm of Ag was deposited by thermal evaporation to form the source and drain. The channel length and width of the shadow mask used for the electrode were 50 and 1000 μm , respectively. The FETs were labeled Pre-F, Dual-F, Post-F, and N-F according to UV irradiation conditions during fabrication. Specifically, Pre-F and Post-F correspond to FETs exposed to UV light before annealing and during annealing, respectively. Dual-F denotes an FET that was annealed following both pre- and post-UV exposure, while N-F indicates an FET that underwent annealing without any

UV exposure. To deposit NFs with consistent quantity and diameter on FETs with different UV irradiation conditions, the substrates for Pre-F, Dual-F, Post-F, and N-F were attached to one drum, and NFs were spun with the same electrospinning parameters.

The ZTO nanofibers were characterized by thermogravimetric analysis (TGA, TGA550, TA Instruments, USA), X-ray diffraction (XRD, D8 ADVANCE, BRUKER, USA), Fourier transform infrared spectroscopy (FTIR, FT/IR-8X, Jasco, Japan), Raman spectroscopy (XploRA, Horiba, Japan), field-emission scanning electron microscopy (FE-SEM, S-4700, Hitachi, Japan), high resolution-transmission electron microscopy (HR-TEM, Talos F200X G2, FEI, USA), and X-ray photoelectron spectroscopy (XPS, Nexsa XPS system, ThermoFisher Scientific, UK). The electrical performance of all FETs was measured at room temperature using a source measurement unit (SMU, Series 2600B, Keithley Instruments, USA). The transfer characteristics were measured with the drain voltage (V_{DS}) of 30 V and the gate voltage (V_{G}) was swept from -20 to $+30 \text{ V}$.

3. Results and discussion

The overall experimental process is shown in Fig. 1(a). The thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) curves of ZTO nanofibers are shown in Fig. 1(b). The TGA was performed from room temperature to 600°C in an air atmosphere at a heating rate of $10^\circ\text{C}/\text{min}$. In the DTG graph, strong peaks were observed at 183.1 and 275.3°C , indicating rapid weight loss. The weight loss process in the TGA graph can be explained in three steps based on the two peaks. In step I (room temperature to 183°C), the weight was reduced from 99.7 to 62.8 % due to evaporation of solvents. In step II (183.03 – 275.34°C), the weight decreased from 62.8 to 36.9 % with decomposition of NC [36,37]. Step III (after 275.34°C) produced a slight weight decrease to 22.1 %. In this region, most of the residues or organic components of NC in the nanofibers had already decomposed, and the metal cations (Zn^{2+} , Sn^{4+}) in the nanofibers were oxidized and condensed into ZTO metal oxide nanofibers. These results indicate that annealing at 350°C is sufficient to remove the residues and organic components from NC and to oxidize and densify the ZTO metal nanofibers.

The FTIR spectra of as-spun nanofibers (ASN); pre-exposed as-spun nanofibers (Pre-ASN); pre-exposed-annealed nanofibers (Pre-N); post-exposed-annealed nanofibers (Post-N); pre-exposed + post-exposed-annealed nanofibers (Dual-N); and non-exposed annealed nanofibers (N-N) are shown in Fig. 1(c). In the FTIR spectra of all samples, the peak positions at 1660 – 1550 , 1280 , and 830 cm^{-1} were assigned to asymmetric and symmetric CH_2 bending vibrations, symmetric NO_2 stretching vibrations, and $\text{O}-\text{NO}_2$ stretching vibrations, respectively, from NC [38,39]. The peak at 1174 cm^{-1} corresponds to metal hydroxide ($\text{M}-\text{OH}$) [40]. The peaks at 497 and 608 cm^{-1} correspond to metal-oxygen ($\text{M}-\text{O}$) bonds, which indicate ZnO and SnO_2 , respectively [41,42]. Notably, the $\text{M}-\text{O}$ network acts as the electron conduction channel [18]. A reduction in the intensity of the NC-related peak was observed after UV irradiation between the ASN and the Pre-ASN sample. This means that the NC polymer underwent partial decomposition due to UV exposure. For the Pre-N, Post-N, Dual-N, and N-N, the peaks by organic bonds were removed, and the peaks corresponding to $\text{M}-\text{O}$ and $\text{M}-\text{OH}$ were formed. This indicated that annealing at 350°C is sufficient to completely remove organic components of polymer and solvent residues as well as to completely transition the metal ion to metal bonds.

The Raman spectra of all samples are shown in Fig. 1(d). Raman spectroscopy was conducted to identify $\text{M}-\text{O}$ bonds in nanofibers. No peaks were observed in the ASN and Pre-ASN. Because these samples were not thermally treated, no detectable metal bonds were present. In contrast, peaks were observed at 299 , 432 , and 616 cm^{-1} for all Pre-N, Post-N, Dual-N, and N-N. The peaks correspond to $\text{M}-\text{OH}$ (bridging OH group, $\text{M} = \text{Zn}$ or Sn) [43,44], ZnO [45], and SnO_2 [46], respectively. This indicates that annealing at 350°C for 3 h was sufficient for the formation of $\text{M}-\text{O}$ and $\text{M}-\text{OH}$ bonds. Nonetheless, the differences in

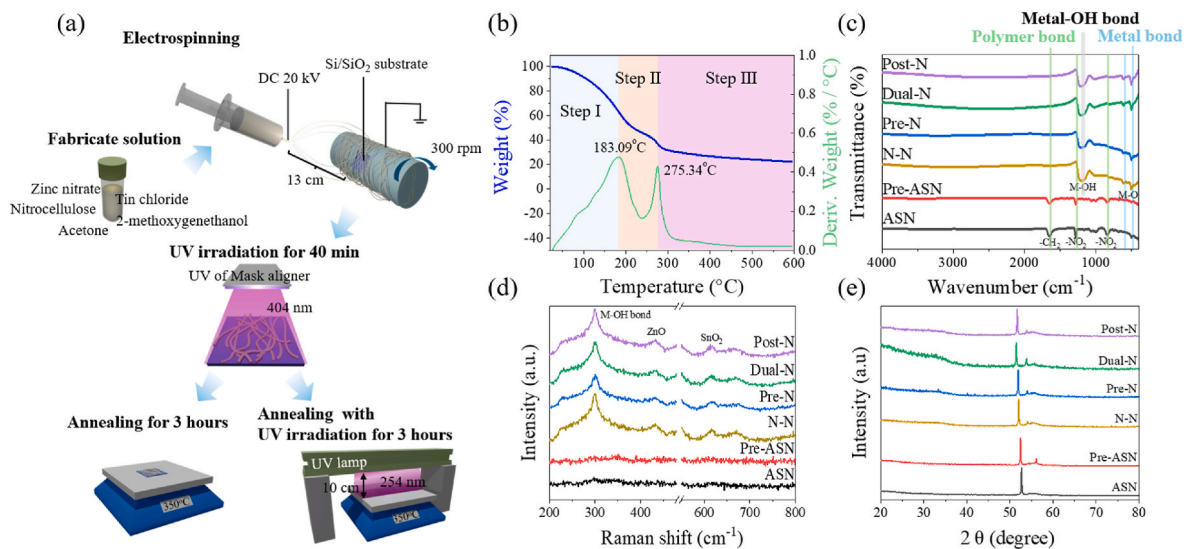


Fig. 1. (a) Schematic illustration of the fabrication of ZTO nanofiber FETs. (b) TGA curve of ASN prior to annealing. (c) FTIR spectra, (d) Raman spectra, and (e) XRD pattern analysis of ZTO nanofibers fabricated under different UV irradiation conditions.

peak intensities were not significant, and the effect of UV exposure could not be determined.

The XRD patterns of ASN, Pre-ASN, Pre-N, Post-N, Dual-N, and N-N are shown in Fig. 1(e). All samples showed distinctive peaks at 52 and 54°, corresponding to the Si/SiO₂ substrate. No peaks corresponding to ZnO or SnO₂ were observed, indicating the amorphous microstructure of all annealed and annealed-UV-irradiated oxide NFs.

Field emission-scanning electron microscopy (FE-SEM) was performed to investigate the diameter and adhesion of ZTO nanofibers fabricated under the various UV irradiation conditions. FE-SEM images are displayed in Fig. 2(a). The average diameters of as-spun ZTO nanofibers and ZTO nanofibers pretreated by 404 nm (only pre-exposure without thermal annealing) were 330 and 308 nm, respectively. The reduction of diameter was ascribed to photodegradation of NC within as-spun ZTO nanofibers. It has been demonstrated that NC can undergo photochemical decomposition, leading to gradual degradation due to the cleavage of ester bonds and, eventually, a lower mean molar mass [47]. The average diameters of Pre-N, Post-N, Dual-N, and N-N were

115, 106, 103, and 106 nm, respectively, indicating no significant differences in nanofiber diameter after thermal annealing. All thermally-treated nanofibers under the different UV irradiation conditions showed a decrease of approximately 200 nm compared to non-annealed nanofibers, suggesting that the organic components and residues of the polymer within the nanofibers were completely decomposed. The adhesion and physical stacking between non-annealed ZTO nanofibers were poor, whereas thermally-treated ZTO nanofibers exhibited improved adhesion between nanofibers. In addition, the SEM images of Pre-N and N-N samples shown in Fig. S4 clearly indicate that the Pre-N sample with pre-exposure treatment resulted in superior adhesion between adjacent ZTO NFs and between ZTO NFs and dielectric layers compared with the non-exposure one [23]. Enhanced adhesion led to reduction of interface trap density between dielectric layer and nanofibers, allowing the FET to produce uniform and improved electrical performance [23,48,49].

HR-TEM and elemental mapping analysis were performed to investigate the microstructure and elemental component of ZTO nanofiber in

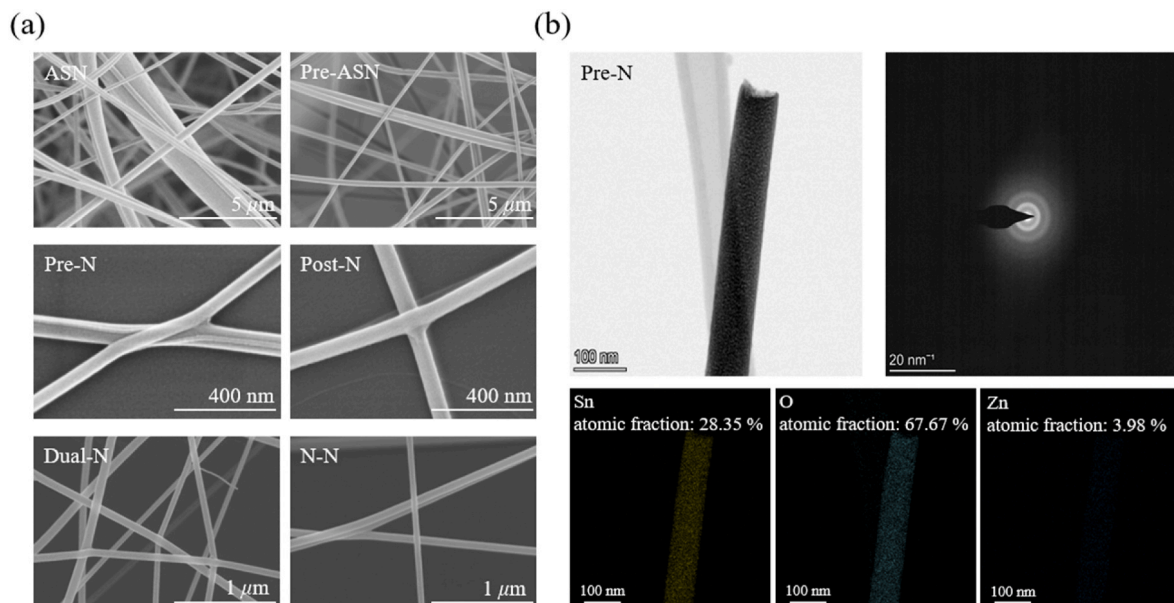


Fig. 2. (a) FE-SEM images of ZTO nanofibers treated under different UV irradiation conditions. (b) TEM and elemental mapping images of Pre-N.

Pre-N, and the results are displayed in Fig. 2(b). The 83-nm ZTO nanofiber was chosen as an analysis target. Multiple diffusing rings were observed, indicating the amorphous phase of ZTO NFs. The Sn, Zn, and O were evenly distributed within the nanofibers as detected by EDS mapping. The atomic fractions of Sn, Zn, and O in the nanofiber were 28.35, 3.98, and 67.67 %, respectively.

To investigate the effect of UV light irradiation, the electrical performances of ZTO NF-based FETs fabricated under the different UV irradiation conditions were compared and are shown in Fig. 3. All fabricated FETs had the same nanofiber density (channel coverage = $0.16 \mu\text{m}^{-1}$) and were annealed at 350°C for 3 h. Fig. 3(a) presents a photograph and a schematic illustration of the FET structure, which features an inverted staggered TFT device structure.

Transfer curves of the FETs fabricated under different UV irradiation conditions are shown in Fig. 3(b). The N-F did not exhibit adequate switching characteristics due to poor adhesion between nanofibers and the dielectric layer. Under poor interfacial contact between a channel layer and a dielectric, oxygen vacancies (V_o) can be formed at the interface due to the structural mismatch between amorphous oxide nanofibers and SiO_2 , which has structural disorder and weak metal oxygen [50]. These interfacial V_o act as donors and abundant V_o due to nature of amorphous oxide nanofibers induce increase of carrier concentration, resulting in metal-like behavior [51,52]. In contrast, all UV-treated FETs exhibited clear switching characteristics. This was attributed to improved interfacial adhesion by UV irradiation. It previously has been demonstrated that UV irradiation improves adhesion properties and enables effective modulation of electrical characteristics [23].

Extracted electrical parameters such as on/off current ratio (I_{on}/I_{off}), saturation mobility (μ_{sat}), threshold voltage (V_{th}), and density of interface traps (N_t) for Pre-F, Post-F, Dual-F, and N-F are summarized in Fig. 3 (c) and d. The μ_{sat} was calculated from the following relationship:

$$\mu_{sat} = 2L \left(\partial \sqrt{I_D} / \partial V_G \right)^2 / W^* C_i \quad (1)$$

where C_i is the dielectric capacitance per unit area, and L and W^* are channel length and effective channel width, respectively. The W^* is defined as the number of nanofibers between the two electrodes and the average diameter of the nanofibers, which is described in Eq. S(1).

The N_t exhibits trap density between active and dielectric layers [52], calculated as

$$N_t = C_i (q \cdot SS \cdot \log(e) / kT - 1) / q \quad (2)$$

Here, k is the Boltzmann constant, T is the absolute temperature, SS is subthreshold swing related to N_t [52], and q is the elementary charge. Among all FETs, Pre-F exhibited the best electrical performance, whereas N-F showed the worst. The Pre-F showed an I_{on}/I_{off} of 5.84×10^6 , V_{th} of -0.1 V , μ_{sat} of $0.63 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, SS of 1.8 Vdec^{-1} , and N_t of $6.3 \times 10^{12} \text{ cm}^{-2}$. Fig. S2 shows the distribution of the transfer curves and electrical parameter variations of the several Pre-F devices. The Post-F exhibited slightly lower electrical performance. The Post-F had I_{on}/I_{off} of 4.99×10^6 , V_{th} of 0.5 V , μ_{sat} of $0.11 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, SS of 3.98 Vdec^{-1} , and N_t of $1.42 \times 10^{13} \text{ cm}^{-2}$. The Dual-F showed an I_{on}/I_{off} of 1.25×10^5 , V_{th} of 5 V , μ_{sat} of $0.11 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, SS of 4.5 Vdec^{-1} , and N_t of $1.6 \times 10^{13} \text{ cm}^{-2}$. Dual-F showed further degradation compared to Post-F, indicating that it underwent greater deterioration due to the high-energy damage of short-wavelength UV (254 nm). The N-F showed an I_{on}/I_{off} of 1.36×10^2 and μ_{sat} of $0.25 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$, other parameters could not be extracted. These results confirmed that different UV irradiation conditions strongly influenced FET electrical performance. Fig. 3(e) and (f) show the output characteristics of N-F and Pre-F, respectively. Despite the positive shift of I_D at low V_D probably due to the photo generated carriers under ambient measurement condition, both output curves clearly exhibit n-type behavior and current saturation induced by the pinch-off effect.

Pre-F and N-F were compared to confirm the effect of pre-exposure. As mentioned above, pre-exposure enabled the FETs to exhibit switching characteristics. This is attributed to improved adhesion between the nanofibers and the dielectric layer due to UV irradiation, which reduces the interfacial defect density [53]. Nevertheless, when comparing

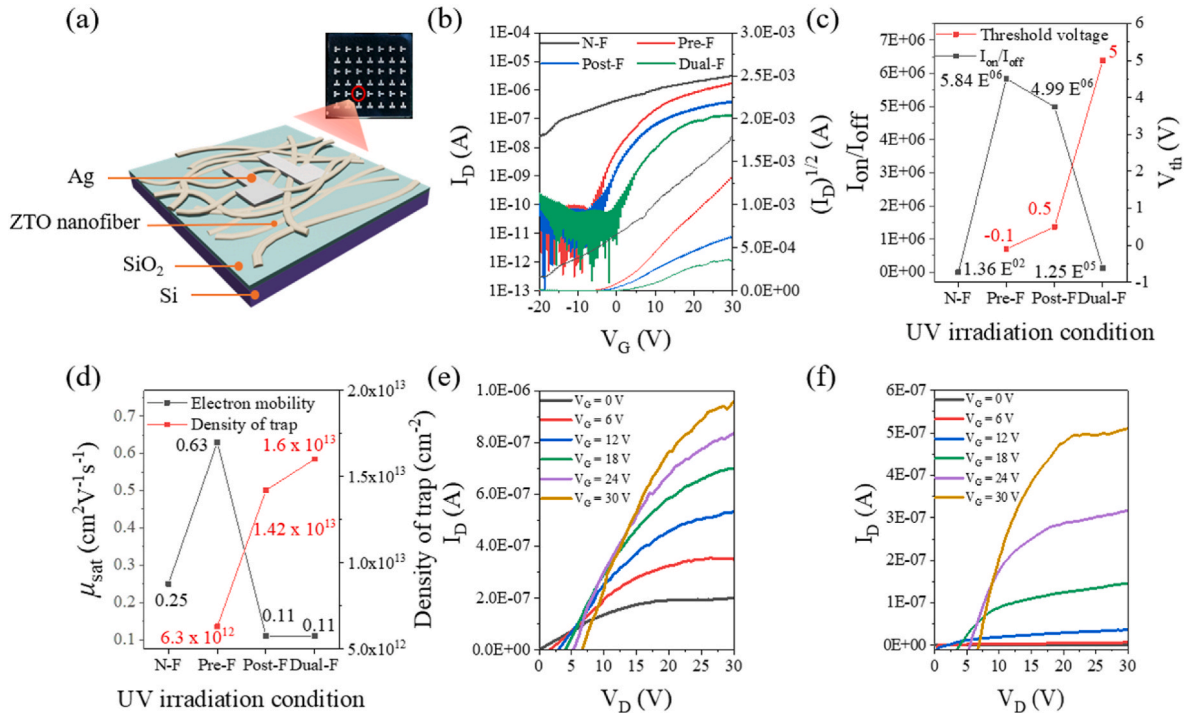


Fig. 3. (a) Photograph and illustration of the ZTO nanofiber FET based on the Si/SiO₂ substrate. (b) Transfer curve and (c), (d) electrical characteristics data of ZTO nanofiber FETs fabricated with different UV irradiation conditions: (c) on/off current ratio and threshold voltage, and (d) saturation mobility and density of trap. Output characteristic curves of (e) N-F and (f) Pre-F.

Dual-F and Post-F, with and without pre-exposure, the I_{on}/I_{off} (from 4.99×10^6 to 1.25×10^5), SS (from 3.98 to 4.5 Vdec^{-1}), and N_t (from 1.42 to $1.6 \times 10^{13} \text{ cm}^{-2}$) of Dual-F deteriorated, while V_{th} shifted positively. The increase in N_t was attributed to trap formation within the active layer, which was induced by UV irradiation during the pre-exposure step [54]. The UV decomposed polymers in the nanofibers, and traps were generated in these decomposed regions during the annealing process [55]. These trap states hinder carrier transport, degrading the general electrical performance [53]. The observed positive V_{th} shift is caused by decreasing in carrier concentration due to the high trap density [53]. In summary, pre-exposure improves adhesion of nanofibers but simultaneously induces significant trap formation in the channel.

To clarify the post-exposure effect, Pre-F and Dual-F were compared. Compared to Pre-F, I_{on}/I_{off} (from 5.84×10^6 to 1.25×10^5), μ_{sat} (from 0.63 to $0.11 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$), SS (from 1.8 to 4.5 Vdec^{-1}), and N_t (from 6.3×10^{12} to $1.6 \times 10^{13} \text{ cm}^{-2}$) of Dual-F were degraded. The increases in SS and N_t were attributed to the photodecomposition of weak chemical bonds in the active layer induced by high energy UV irradiation. The photon energy used for post-exposure was calculated by the following equation:

$$E = hc/\lambda \quad (3)$$

The energy of 254 nm UV used for post-exposure was 4.89 eV. This is sufficient to break Zn-O and Sn-O bonds, which have bond energies for diatomic formation of 1.5 eV and 2.1 eV, respectively [56,57]. These broken bonds generated defect states that act as carrier traps, degrading the electrical performance of the FETs. It previously has been reported that 254 nm UV can damage the Si/SiO₂ interface, leading to changes in electrical characteristics [58]. This can generate excess carriers both in the channel and at the channel-dielectric interface, further deteriorating the device performance [58]. As a result, FETs subjected to

post-exposure exhibit inferior performance compared to the pre-exposure FET. Moreover, Dual-F showed the most severe degradation due to the cumulative effects of the previously mentioned trap formation and interfacial damage.

X-ray photoelectron spectroscopy (XPS) was performed for all ZTO NFs fabricated under the different UV irradiation conditions. The 284.6 eV peak of C 1s was used as a reference point to calibrate all data. The O 1s XPS spectra of Pre-N, Post-N, Dual-N, and N-N are shown in Fig. 4. Three deconvoluted peaks located at 530.4 ± 0.2 , 531.3 ± 0.2 , and 532.2 ± 0.2 eV are assigned to oxide lattices M – O (O_I) and V_o (O_{II}) and hydroxyl oxygen species M – OH (O_{III}), respectively. Among the ZTO NFs treated by UV, Pre-N showed the highest M – O and V_o contents, indicating a well-densified M – O network with a reasonable carrier concentration. This could explain why the optimal electrical performance was obtained for the Pre-F device as in Fig. 3. Compared with the N-N, the M – O of the Pre-N increased (61.69–62.42 %), while V_o decreased (24.47–22.63 %). This is attributed to pre-exposure inducing densification and condensation of metal [19,59]. The M – O (58.61 % for Post-N, 56.11 % for Dual-N) and V_o (21.17 % for Post-N, 21.84 % for Dual-N) of the Post-N and Dual-N were reduced compared to those of the N-N. In contrast, the M – OH (19.22 % for Post-N, 22.05 % for Dual-N) of those increased to N-N (13.83 %). The decrease in M – O bonds was due to the decomposition of weak chemical bonds by a high energy (4.8 eV) of 254 nm for post-exposure [21]. The decomposed metal cations combined with the OH bonds within the nanofibers, causing the UV-exposed ZTO NFs to form more M – OH bonds than the N-N [60,61]. Additionally, the decrease in V_o was observed for UV-irradiated ZTO NFs. Synchronizing thermal-UV treatment probably induced a reduction in defect sites associated with oxygen vacancies, formation of chemical bonds, and reorganization of dissociated atoms [21,59]. This can explain the on-current reduction in UV-exposed ZTO NF-based FET devices

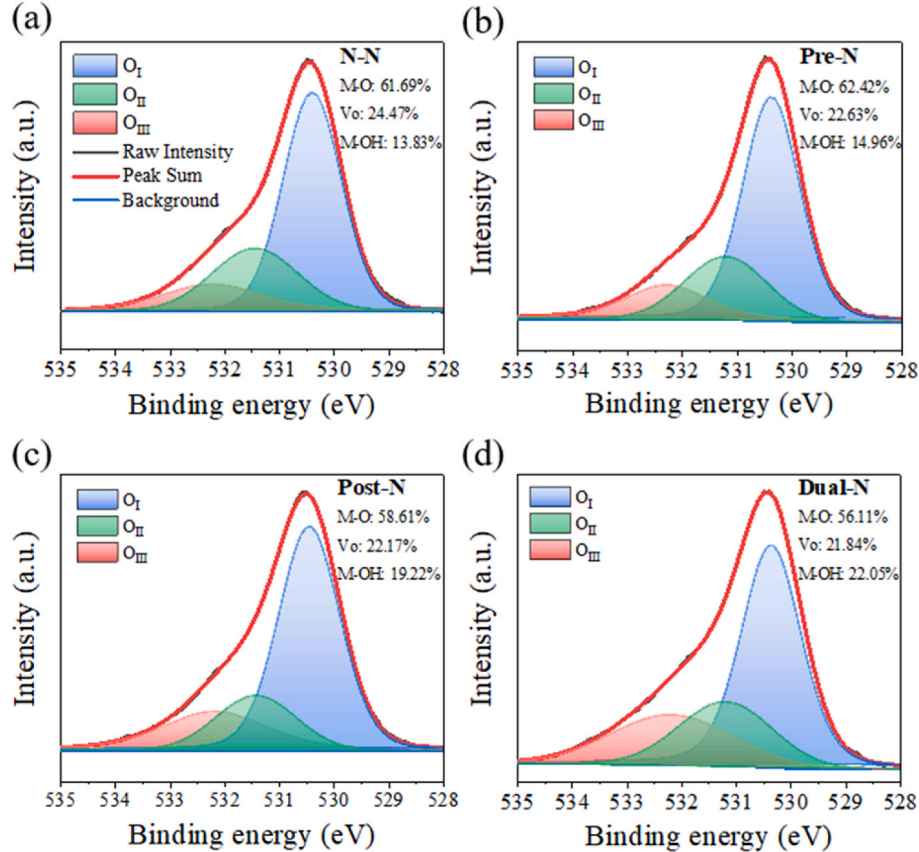


Fig. 4. XPS spectra of O 1s and atomic percentage analyses of the oxygen component of ZTO nanofiber fabricated with different UV irradiation conditions: (a) N-N, (b) Pre-N, (c) Post-N, and (d) Dual-N.

previously mentioned in Fig. 3(b).

The influence of nanofiber density on the electrical performance of FETs was studied by adjusting the number of strokes. Strokes refer to the horizontal back-and-forth movements of the electrospinning nozzles, which are directly related to the total electrospinning duration. Each stroke represents one complete round trip of the nozzle stage. The number of strokes was 10, 15, 20, and 25 strokes, and the nanofiber density values corresponding to each condition were 0.11, 0.16, 0.21, and $0.27 \mu\text{m}^{-1}$, respectively, as shown in Fig. S3. The FETs were fabricated based on Pre-F, which exhibited the best electrical performance, and all FETs were annealed at 350°C for 3 h.

The transfer curves and extracted electric parameters of Pre-F with different nanofiber densities are shown in Fig. 5. Both on-state current (I_{on}) and off-state current (I_{off}) increased with increasing stroke. As the density of nanofiber increased from 0.11 to $0.27 \mu\text{m}^{-1}$, I_{on} increased from 4.5×10^{-7} to 5.17×10^{-6} , and I_{off} increased from 1.43×10^{-13} to 2.72×10^{-8} . This increase was due to the increasing carrier concentration in the active layer with increasing nanofiber density, which resulted in a negative shift of V_{th} and improvement of μ_{sat} , as shown in Fig. 5(a) and (b). The FET with a density of $0.27 \mu\text{m}^{-1}$ exhibited metallic characteristics due to excessive carriers. The increase in I_{on} was relatively small compared to the increase in I_{off} . This was probably attributed to the rising contact resistance between nanofibers as the nanofiber density increased, which suppressed the increase in I_{on} . This is why $I_{\text{on}}/I_{\text{off}}$ decreases when the nanofiber density was more than $0.16 \mu\text{m}^{-1}$, as shown in Fig. 5(c).

The transfer curves and electrical parameters of FETs for different annealing times are presented in Fig. 6. All FETs were fabricated based on a Pre-F. As shown in Fig. 6(a), 1 h annealing exhibited conducting behavior due to insufficient annealing accompanied with many possible structural defects regarding V_{O} . On the other hand, the NF-based FETs annealed for more than 2 h exhibited switching characteristics, implying that annealing required at least 2 h for proper device operation. Both I_{on} and I_{off} decreased and then increased around the 3 h annealing time point, suggesting that 3 h annealing showed the optimal electrical performance. Prolonged annealing may contribute to oxygen loss or the generation of oxygen vacancies with a higher carrier concentration resulting in less effective gate control [62,63]. Fig. 6(b) shows the electrical performance parameters of ZNFETs at different annealing times. The FET annealed for 2 h and 4 h exhibited poor electrical performance, with a significantly negative V_{th} and poor switching characteristics ($I_{\text{on}}/I_{\text{off}} \sim 10^2\text{--}10^3$). The μ_{sat} gradually improved with increasing annealing time, as shown in Fig. 5(c). This improvement was attributed to the increase in M–O bonds and the reduction in trap states (observed in the 3 h-annealed FET). The FET annealed for 4 h exhibited a high

electron mobility ($\mu_{\text{sat}} \sim 10.08 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$), likely due to the previously mentioned enriched carrier concentration; however, its inferior switching behavior is not ideal for ZNFETs [61,64]. Among all the FETs, the device annealed for 3 h exhibited the highest $I_{\text{on}}/I_{\text{off}}$, indicating the optimal condition for device fabrication.

4. Conclusion

The ZTO nanofiber-based FETs were successfully fabricated at low annealing temperature under the synergetic effect of UV exposure at various conditions to optimize their electrical performance. Among these, the Pre-F, which was irradiated with UV prior to annealing, exhibited the optimal performance, achieving an $I_{\text{on}}/I_{\text{off}}$ of 5.84×10^6 , with decent saturation mobility, low V_{th} of -0.1 V , SS of 1.8 Vdec^{-1} , and N_t of $6.3 \times 10^{12} \text{ cm}^{-2}$. We confirmed that the electrical performance of the FET was significantly affected by UV irradiation conditions. Comprehensive analysis using FTIR, Raman, XRD, FE-SEM, TEM, and XPS were performed to investigate the effects of UV irradiation conditions on ZTO nanofibers and on electrical performance. These results suggest that proper control of UV irradiation can enhance the device performance. This low-temperature ZTO NF-based FET could be considered a promising candidate for future development of flexible electronic devices.

CRediT authorship contribution statement

Minseo Kang: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Tan Tan Bui:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Ji-Hoon Lee:** Writing – review & editing, Supervision, Resources, Formal analysis.

Funding sources

National Research Foundation (NRF, RS-2023-NR076361, RS-2019-NR040079).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

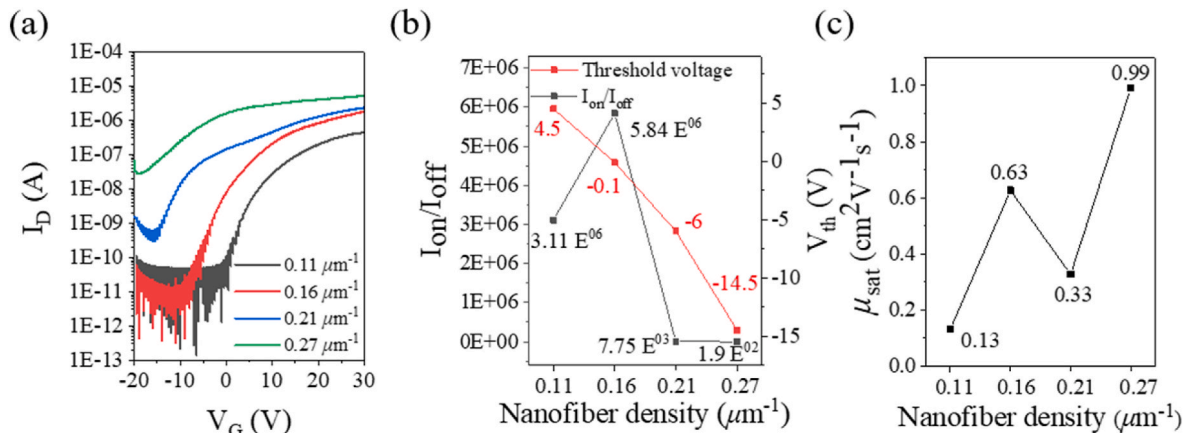


Fig. 5. (a) Transfer curve of ZTO nanofiber FET devices with different densities of nanofibers. The stroke is an indicator of the density of nanofibers. The nanofiber density increases with increasing stroke. Electrical performance of ZTO nanofiber FETs: (b) on/off current, threshold voltage, and (c) saturation mobility. All ZTO nanofiber FETs were fabricated by annealing without UV irradiation after pre-exposure (Pre-F).

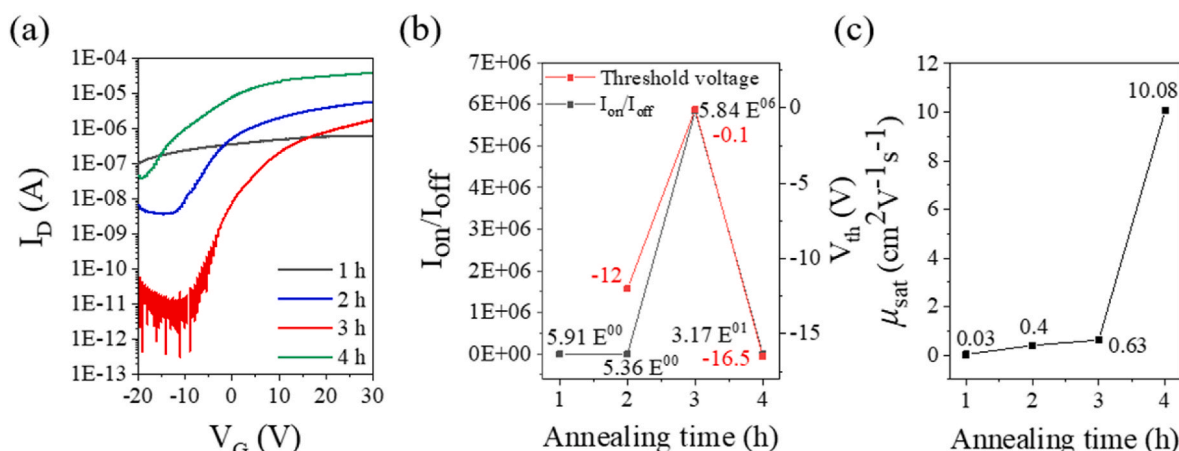


Fig. 6. (a) Transfer curves of ZTO nanofiber FETs annealed at different times. Electrical characteristics data of ZTO nanofiber FETs with different annealing times: (b) on/off current, threshold voltage, and (c) saturation mobility. All ZTO nanofiber FETs were fabricated by annealing without UV irradiation after pre-exposure (Pre-F).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.mssp.2025.109909>.

Data availability

Data will be made available on request.

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