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Fabrication of Micro/Nanometer-Channel by Near-Field ElectroSpinning

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***Abstract*- Direct-written polymer micro/nanofiber from Near-Field ElectroSpinning (NFES) was utilized as shadow-mask to fabricate uniform micro/nanometer-channel. Both Single straight microfiber (line-width 2~10μm) and nanofiber (diameter 200~800nm) were direct-written on the substrate with the NFES setup, and then 2-nm-thick titanium adhesive layer and 10-nm-thick gold layer were sputtered on the substrate successively. By the ultrasonication process in acetone and de-ionized water, the polymer fiber was removed and micro/nanometer-channel with gap width ranging from 7μm to 700nm was formed. The fabrication process and related technical issues were also outlined in this work. The experimental results revealed that the micro/nanometer channel had a good uniformity, above 90% of the gap length value lied within the deviation range of ±3%. This simple and facile method can be used to define the uniform micro/nano channel for organic thin film transistors.**

***Index terms*- Near-Field Electrospinning, Micro/nanofiber, Micro/Nanometer channel**

INTRODUCTION

Organic thin film transistors (OTFTs), as the fundamental building blocks for low-cost organic electronics, have attracted increasing attention. One of the key parameters in an OTFT is the channel length L, which is defined by the gap between the source and drain electrodes, controls the performance of the device [1, 2], such as the drain current I_d which is proportional to $1/L$, the maximum switching frequency f and the density of integration N which are both proportional to $1/L^2$. Typically, transistors are fabricated by using photolithography [2] or by depositing metal layer through a stencil [3] when the channel length L is in the order of micrometers. And, Electron-Beam Lithography (EBL) [2, 4] is usually used to obtain the channel with length of sub-micrometer and nanometer order. But these traditional methods are highly cost, complicated and not consistent with the low-cost advantage of organic electronics. At present, researchers have tried many other innovative techniques to gain the gap. Zaumseil [5] et al. used high-resolution rubber stamps to define the channel length ranging from 250μm down to 150nm. Y. Chen [6] et al. combined the Si-etching and evaporation with a high tilting angle to demonstrate OTFTs with channel length of 0.5~10μm. Austion and Chou [7] successfully fabricated 70nm channel length polythiophene transistors by using nanoimprint lithography. Recently, Hideyuki Murata [8] et al. proposed to fabricate a submicron-gap electrode by using an electrospun single fiber as shadow-mask. This is a simple and cost-effective method, yet the nanofiber used as shadow-mask was obtained through the post-stretching process, which increased the complexity and uncertainty of fabrication process.

In this paper, Direct-write (DW) technology [9] based on Near-Field ElectroSpinning (NFES) [10] was utilized to obtain single straight micro/nanofiber directly, and used as shadow-mask to fabricate micro/nanometer-channel. The gap length of micro/nanometer-channel was in the range of 700nm to 7μm. The fabrication process and related technical issues were described, and then the uniformity of micro/nanometer-channel was also evaluated and discussed.

EXPERIMENTAL DETAILS

A schematic illustration of the experiment process was shown in Fig. 1. The single straight micro/nanofiber was direct-written by using the NFES setup shown in Fig. 1(a), which included a spinneret, a high voltages source (DW-P403-1AC, Tianjing Dongwen High Voltage Power Supply Plantn, China) and an XY motion stage (TR10&TR07, Parker Co. Ltd, USA). The anode of high voltage source was connected to the spinneret, and the cathode was connected to the substrate which was grounded. Poly(ethylene oxide) (PEO, M_w=300,000, Dadi Fine Chemical Co., Ltd., China) was dissolved in the blend of 60% vol /40% vol water/ethanol to form 20 wt. % polymer solution, which was used as electrospinning material in this work. Two kinds of spinnerets were used in our experiment: one was the solid copper probe (see Fig. 1(b)) with tip diameter of 40μm; the other was the hollow steel needle (see Fig. 1(c)) with inner diameter of 232μm. When solid spinneret was used, polymer solution was loaded discretely onto the probe with a glass syringe and nanofiber (diameter 200~800nm) could be obtained. When hollow spinneret was used, polymer solution was supplied continuously with a precision syringe pump and microfiber (line-width 2~10μm) could be electrospun. A 0.5-mm-thick silicon wafer coated with a 150-nm-thick silicon dioxide was used as the target substrate, which was fixed on the X-Y motion stage (motion speed 0~1m/s). The distance between spinneret and substrate was 2mm. The schematic process of micro/nanometer-channel was shown in Fig.1 (d) ~ (f): firstly, single straight fiber was electrospun on the substrate directly; secondly, 2-nm-thick Ti adhesive layer and 10-nm-thick Au layer were sputtered on the substrate through a metal mask successively; thirdly, the substrate was soaked in acetone for 24 hours, then ultrasonic

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cleaning in acetone and de-ionized water for 10 minutes, respectively. The micro/nanometer channel could be obtained on the substrate by removing the micro/nanofiber.

Scanning electron microscope (SEM) images were measured with the LEO 1530 Field-Emission Scanning Electron Microscope and the XL30 Field-Emission Environmental Scanning Electron Microscope (ESEM-FEG). Metal layer was sputtered with the magnetron sputtering plant (JC500-3/D).

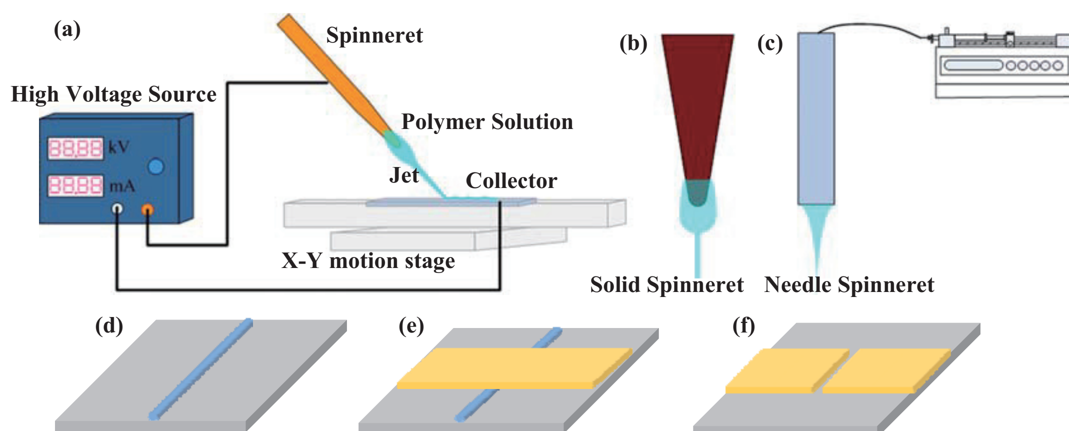

Fig. 1. Schematic diagram showing the process steps to fabricate the micro/nanometer-channel. (a) NFES system setup. (b) solid spinneret. (c) needle spinneret. (d) single straight fiber was directly deposited on the substrate. (e) Ti/Au layer was sputtered on substrate. (f) micro/nanometer-channel was obtained after removing the fiber by ultrasonic cleaning in acetone and de-ionized water.

Results and Discussion

NFES takes the advantage of stable liquid jet region immediately outside the spinneret by shortening the electrode-to-collector distance to 0.5~3mm. Orderly fiber can be deposited on the substrate before the whipping and splitting process. The crucial factor to obtain a single straight fiber is the substrate motion speed. Only when the substrate motion speed is comparable to or higher than the electrospinning speed, could a single straight fiber be deposited on the substrate. Details of NFES could be found in previous reports of our group [9-11]. Figure 2(a) shows the fiber electrospun with hollow spinneret, when the substrate motion speed and applied voltage was 0.6m/s and 2.0kV respectively, and the line-width of fiber was 5.12μm. The fiber electrospun from solid spinneret was shown in Fig. 2(b), when the substrate motion speed and applied voltage was 0.4m/s and 1.7kV respectively, and the diameter of fiber was measured to be 711.2nm.

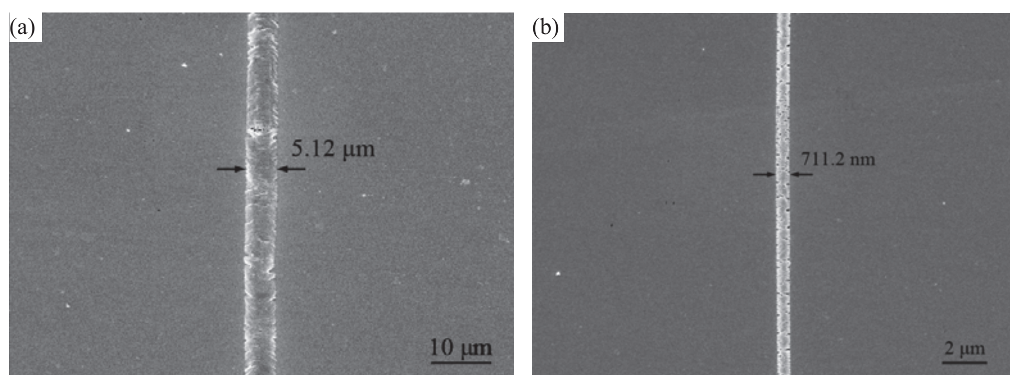

Fig. 2. SEM images of single straight fiber electrospun on the substrate. The scale bars correspond to 10μm and 2μm, respectively. (a) fiber with the diameter of 5.12μm when substrate motion speed and applied voltage is 0.6m/s and 2.0kV respectively. (b) fiber with the diameter of 711.2nm when substrate motion speed and applied voltage is 0.4m/s and 1.7kV respectively.

By using the single straight fiber as shadow-mask, micro/nanometer channel shown in Fig. 3 can be fabricated on the Si/SiO_2 substrate. Figure 3(a) showed the channel with gap length of 2.4μm and Au electrode width of 50μm, and Fig. 3(b) showed the magnified image of the area indicated by a rectangle in Fig. 3(a). The quality of the channel depended strongly on the electrode width, because larger electrode width increased the difficulty for acetone to penetrate and dissolve the polymer fiber. In our experiments, the maximum electrode width for microchannel was about 1mm, and the maximum electrode width for nanochannel was about 400μm. Figure 3(c) and 3(d) showed the channels with measured diameter of 821.5nm and 513.7nm, respectively. Debris of the gold layer can be observed clearly at both sides of the channel, which reflected the lifting-off process of fiber during the ultrasonic cleaning, the arrows in Fig. 3(b) and (d) showed the

debris. Yet for nanochannel, such the debris probably resulted in short circuit between the electrodes. To resolve this issue, the sonication process can be carried out in hot acetone or for a longer time to rub off the debris as far as possible.

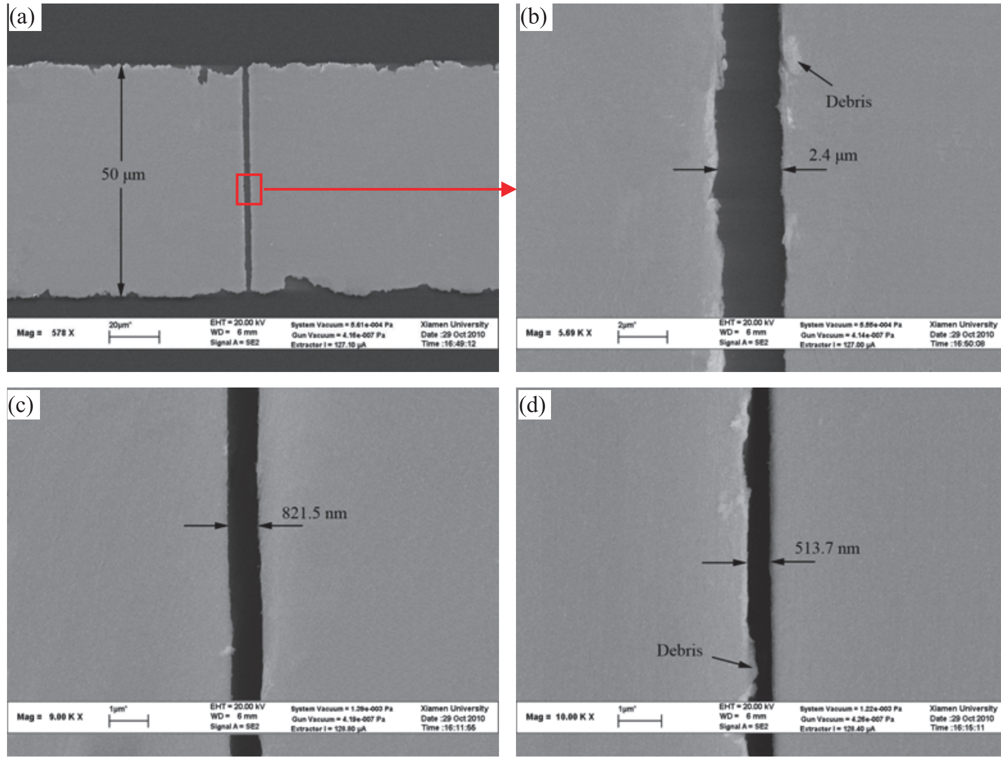

Fig. 3. SEM of the fabricated channels. (a) micrometer channel, the gap length and Au electrode width was 2.4μm and 50μm, respectively; (b) magnified image of the rectangle area in (a). (c) and (d) nanometer channel, the gap length was 821.5nm and 513.7nm, respectively. Debris of gold layer can be observed at both sides of channel, especially in (b) and (d).

Figure 4(a) and Fig. 5(a) showed that the average gap length of channels were 5.27μm and 713.4nm, respectively. The inset in Fig. 4(a) showed the enlarged SEM image of the channel. We randomly measured 60 values of gap length $\boldsymbol{D}$ along the channel to calculate the average gap length $\boldsymbol{D_{av}}$. To evaluate the uniformity of the gap length, we calculated the deviation radio defined by $\boldsymbol{DR}=(\boldsymbol{D}-\boldsymbol{D_{av}})/\ \boldsymbol{D_{av}}$ and gave the histograms of the deviation range, as shown in Fig. 4(b) and Fig. 5(b). For 5.27-μm-length channel, 91.7% of gap length value lied within the deviation range of ±3%. In case of 713.4-nm-length channel, 90% of gap length value lied within the deviation range of ±3%. The experimental results showed that the micro/nano-channel fabricated from direct-written micro/nanofiber had good uniformity.

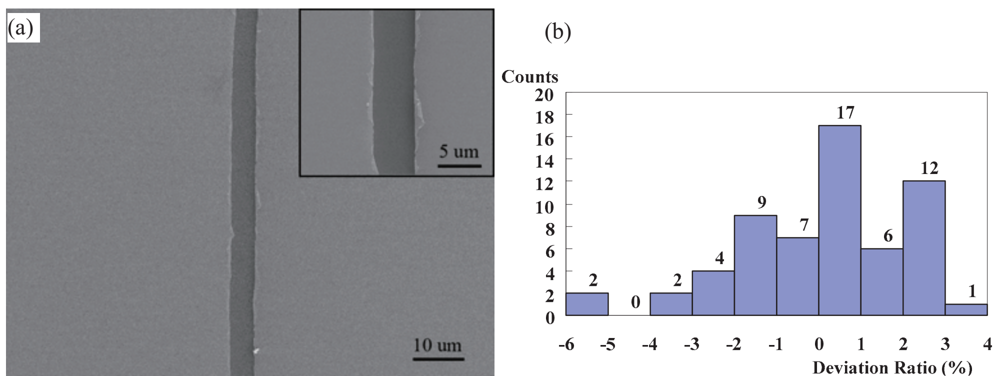

Fig. 4. (a) SEM image of the micrometer channel with gap length of 5.27μm. The inset in (a) showed the enlarged SEM image of the channel. (b) Histogram of the deviation range of the gap length in Fig. 4(a).

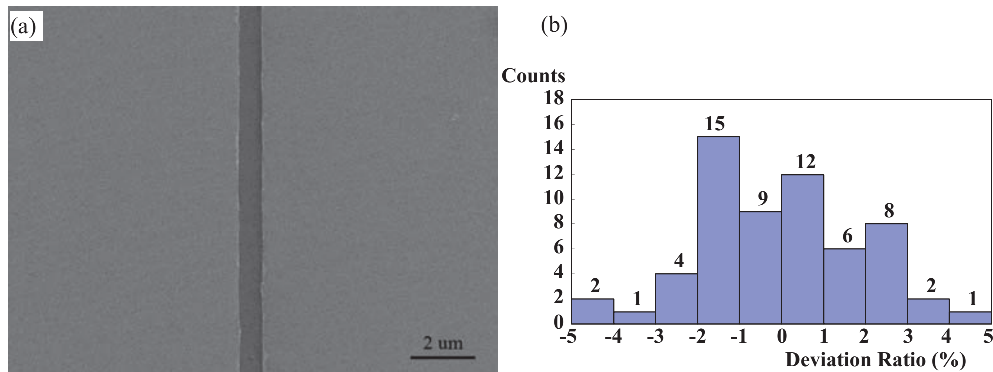

Fig. 5. (a) SEM image of the channel with gap length of 713.4nm. (b) Histogram of the deviation range of the gap length in Fig. 5(a).

CONCLUSIONS

In a summary, direct-written polymer micro/nanofiber by NFES was utilized as shadow-mask to fabricate uniform micro/nanometer-channel. Single straight microfiber (line-width 2~10μm) and nanofiber (diameter 200~800nm) can be deposited on the substrate with the NFES setup, and then 2-nm-thick titanium adhesive layer and 10-nm-thick gold layer were sputtered on the substrate successively. By the ultrasonic cleaning in acetone and de-ionized water, the polymer fiber was removed and micro/nanometer-channel with gap width ranging from 7μm to 700nm can be formed. Experimental results showed that the micro/nanometer channel had a good uniformity, above 90% of gap length value lied within the deviation range of ±3%. This simple and facile method can be used to define the uniform channel for organic thin film transistors. Further process parameter optimization would be done to increase the quality of the micro/nano-channel in our work, such as narrower gap length and higher uniformity.

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