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# Direct-Write Micro/Nano-Structure For Flexible Electronic Manufacturing

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***Abstract* — This article focuses on optimizing the electrospinning parameters, and developing a new method of Direct-Write (DW) micro/nano-structure based on Near-Field Electrospinning (NFES) for flexible electronic manufacturing. NFES is a new way to realize controllable electrospinning and precision-positioning of nanofiber, by which nano-structure with diameter from 50nm to 500nm can be fabricated orderly and accurately. A tungsten electrode with tip diameter of 25µm is used to DW nano-structure, with the minimum bias voltage 600V, minimum electrode to collector distance 500µm. A micro-structure DW system is designed, by which micro-structure with diameter of several micrometers can be drawn. In this work, a needle tube of 232µm inside diameter is used as spinneret, electrode to collector distance is various from 2mm to 10mm, and the collector moving speed ranges from 0.07m/s to 7m/s. The DW process and character of micro-structure such as line width, smoothness and thickness can be controlled by optimizing the electrospinng parameters. The DW micro/nano-structure is continuous and smooth, which can be drawn on expected site and in expected direction with accurate dimension. The new method based on NEFS with the advantage of narrower line width and smoother structure than traditional flexible electronic manufacturing technologies, which is more suitable for the development of flexible electronic manufacturing.**

*Keywords* ***—Direct write, Flexibe electronic manufacturing, Mano/micro sturecture, Near-field electrospinning***

## I. INTRODUCTION

Flexible electron has become one of the hotspots for electronic industry development [1-3], such as flexible panel display, RFID and flexible artificial skin. At present, the most popular manufacturing technologies for flexible electronic are screen printing, inkjet printing or etching. There are some common disadvantages for all above technologies, such as difficult to reduce line width and further optimize process parameters. For example, the minimal liquid drop for inkjet printing is 10pl and the narrowest line width is 50µm. Now, the innovation of manufacturing is one of the issues for flexible electronic manufacturing. In this work, a new and simple method of nanofabrication based on Near-Field Electrospinning (NEFS) [4] is studied for the application in the flexible electronic manufacturing.

Electrospinning based on electrostatic driving mechanism is a very simple and versatile process, by which long, continuous and smooth nanofiber/micro-structures with diameter/width rang from 10nm to 10µm, can be produced [5, 6]. The technology has attracted much attention recently due to the ease with which nanometer diameter fibers can be produced from either natural or synthetic [7-10] polymer. The nanofibers fabricated by the process of electrospinning possess the desired high surface area, controllable porosity and mechanical properties [11]. Non-woven mat or aligned fibers have potential application such as bio-scaffold, wound dressing, filtrations, defense dress and composite materials [12, 13]. However, it is difficult for traditional electrospinning to be controlled to obtain addressed nanofibers, which has become the obstacle to expand application field of electrospinning. NFES [4], which realized the controllable DW and serial deposition of nanofibers, has overcome the shortcomings of traditional one. DW micro/nano-structure based on NFES with accurate dimensions and deposition, of which the line width or diameter is various form tens of nanometers to several micrometers. DW micro/nano-structure is smooth, continuous, of which the line width is narrower. For these special characters, DW technology on NFES has potential to be utilized as a new method for flexible electronic manufacturing.

In this work, a DW experiment system is provided. Parameters optimization of DW, line width, smoothness and thickness of DW micro/nano-structure are studied to investigate the application of DW technology for flexible electronic manufacturing.

## II. EXPERIMENTS

### *A. The Experiment Principle*

There are two stages in the electrospinning process, the first one is the straight liquid jet with diameter of several micrometers, and the second one is the area of whipping and splitting which make the fibers thinner [14, 15]. NEFS [4] takes the advantage of the stable liquid jet region immediately outside the spinneret for controllable position deposition by shortening the electrode-to collector distance. Figure 1A shows the schematic setup of NFES, the electrode to collector distance *h* is in the range of 500µm~3mm and the stable liquid jets region is utilized for controllable deposition. Needle tube is replaced by tungsten probe tip of 25µm tip diameter as spinneret. Applied electrostatic voltage is reduced due to the short electrode to collector distance while the electrical field in the tip region maintains the strength in the range of $10^7$ V/m as those used in conventional electrospinning to activate the process. Discrete droplets of polymer solution are supplied in a manner analogous to that of a dip pen by immersing and pulling the tungsten electrode in to and out of the polymer solution.

Based on NFES theory a new electrospinning process is designed, in which needle tube is used as spinneret and electrode to collector distance *h* is shorted to 2mm~10mm as shown in Figure 1 B. For the shorter electrode to collector

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distance, the straight line jet under Taylor cone can be employed to realize micro-structure controllable deposition. The length of first stage with straight line jet is affected by the imposed flow rate *Q*, current *I* and the voltage drop *U* between the spinneret and collector [16, 17]. The electrostatic field between the electrode and the collector is about 1.5kV/mm, a straight line with length of 6mm and jet radius less than 8μm can be obtained outside the spinneret before whipping and splitting[18, 19]. In this work, gap between electrode and collector is adjusted from 2mm to 10mm, and the applied voltage is various from 2kV to 5kV.

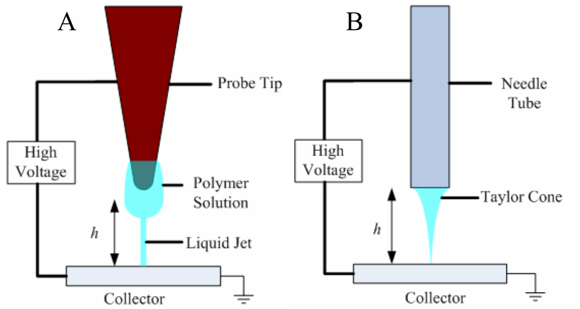


Figure1 A: Schematic diagram of NFES, the polymer solution is attached to the tip of the tungsten electrode in a manner analogous to that of a dip pen. B: New electrospinning process with needle tube used as spinneret and shorter electrode to collector distance (2mm~10mm).

## B. *DW Experimental System*

A DW experimental system based on NFES is designed to study the parameter optimization of electrospinning process, and the character of DW micro-structure. Figure 2 shows the schematic diagram of the experiment system. The experiment system includes: precision syringe pump, high-voltage static transformer, rotary stepper motor and linear stepper motor. The speed of rotary stepper motor can be adjusted from 0.07m/s to 7m/s, and the speed of linear stepper motor is various from 0.001m/s to 0.1m/s. The voltage of high-voltage power supply can be controlled between 0V to 15kV. The electrode to collector distance can be adjusted from 2mm to 10mm. The collector (silicon substrate) for DW micro-structure deposition is laid at the edge of the rotary stepper motor, so the collector moving speed mentioned below refers to the edge moving speed of the rotary stepper motor.

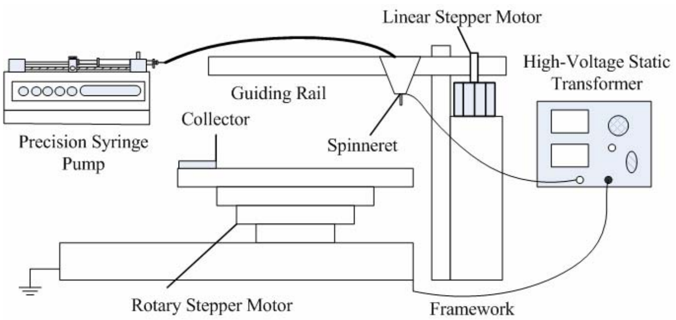


Figure 2 Schematic diagram of micro-structure direct-write system.

Poly (ethylene oxide) (PEO) is one of the most extensively studied polymer for electrospinning [20, 21], and has been studied extensively in electrospinning onto silicon-based collectors for possible system integration with MEMS (microelectromechanical systems) and microelectronics, is used to electrospinning in this work. The concentration of PEO (Tianjin, Da Di Fine chemical Engineering Co., *My* 300,000g/mol) solution used in this work is from 0.5%wt to 22%wt PEO in 50%wt/50%wt water/ethanol solvent. Tungsten electrode with tip diameter of 25μm and needle tube with inside diameter of 232μm are both utilized as spinneret in this work, by which nano-structure and micro-structure can be direct-written respectively.

# III. RESULTS

## A. *DW Nano-Structure*

NFES takes the advantage of a stable liquid jet region immediately outside the spinneret for position controllable deposition by shortening the electrode-to-collector distance. When a tungsten probe tip with diameter of 25μm used as spinneret, nanofiber with diameter from 50nm to 500nm can be direct-wrote on the silicon substrate. In electrospinning process, liquid polymer solution is supplied in a manner analogous to that of a dip pen.

When the electrospinning speed is faster than collector moving speed, helical structure would occur. Figure 3A shows the nanofibers with helical structure are direct-written on the silicon substrate. Straight nanofiber without helical structures and wave can be drawn on the substrate if its moving speed is compatible with the electrospinning speed as shown in Figure 3B.

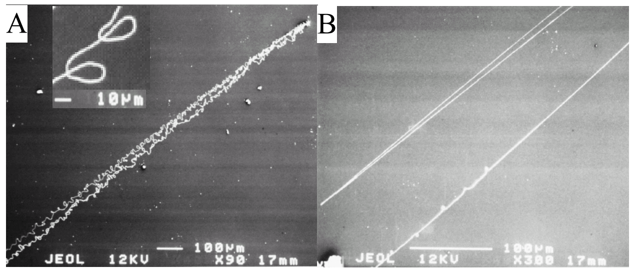


Figure 3 Nanofibers collected on silicon substrate. PEO solution concentration used here is 3wt%, electrode gap-width is 500μm, and the applied voltage is 600V. A, nanofibers on moved silicon substrate, the line is the moved direction, the insets are helical structures; B, the straight nanofibers without helical structures.

## B. *DW Micro-Structure*

Micro-structures with line width of several micrometers can be drawn on the substrate directly, when a needle tube used as spinneret. The polymer solution is supplied by precision syringes pump, so experiment system with needle tube can work continuously for longer time.

In DW process the liquid polymer solution vaporizes less time than traditional electrospinning, for the electrode to collector distance (2mm~10mm) is shorter. Figure 4 shows micro-structures drawn on substrate directly, the applied voltage is 2kV and electrode to collector distance is 2mm. In Figure 4A, the line width of narrow thin film is 2.32μm, PEO solution concentration is 20% and collector moving speed of is 0.7m/s. In Figure 4B, the collector moving speed is 1.7m/s, PEO solution concentration is 20% and the line width is

3.203μm. In Figure 4C and D the PEO solution concentration is 22%, and the collector moving speed is 1.7m/s, 7m/s respective. The line width of micro-structure in Figure 4 C and D is 7.602μm and 7.523μm. The line width of micro-structure will become wider with increasing the polymer solution concentration and collector moving speed. It can be seen that from Figure 4A and B, the surface will become smoother and the thickness will become smaller, when accelerate the collector moving speed. There are particle-like structures appear on the surface of micro structure as shown in Figure 4D, when the collector moving speed (7m/s) become much higher. The surface smoothness and thickness of micro-structure would be affected by the collector moving speed, PEO solution concentration, so micro-structure with smoother surface can be gained by optimizing these parameters.

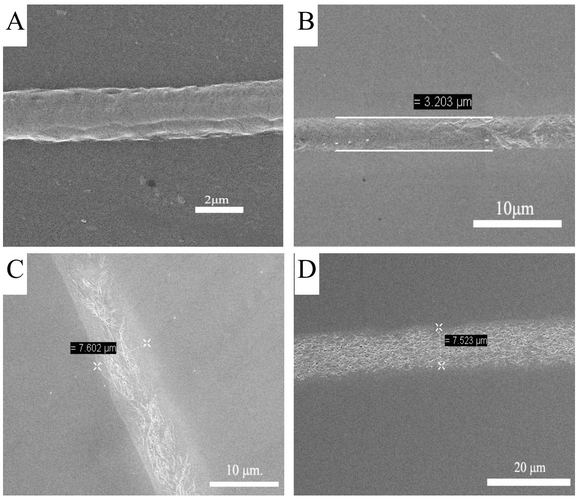


Figure 4 Direct-write micro-structure drawn on substarte, the needle tube with inside diameter of 232 μm used as spinneret, the applied voltage is 2kV and electrode gap width is 2mm. PEO concentration is 20% in A, B, and 22% in C, D. Collector moving speed is 0.7 m/s in A, B, C, and 7m/s in D. The line width of micro-structure is 2.32μm, 3.203μm., 7.602μm and 7.523μm in A, B, C and D.

Parallel micro-structure can be collected, by coordinating the moving speed of rotary stepper motor and linear stepper motor. When the collector moving speed is compatible with the electrospinning ratio, parallel micro-structures without curve can be drawn on substrate as shown in Figure 5. The collector moving speed is 1.6m/s, 2.2m/s, 2.5m/s and 7m/s in Figure 5A, B, C and D respective, the moving speed of linear stepper motor is 0.1m/s, PEO concentration is 20%, electrode to collector distance is 2mm and applied voltage is 2.3kV. With the collector moving speed increasing, distance between two micro-structures and surface smoothness of thin film micro-structure would become more uniform. Coordinating the moving speed of rotary stepper motor and linear stepper motor, micro-structures with precision position deposition can be gained.

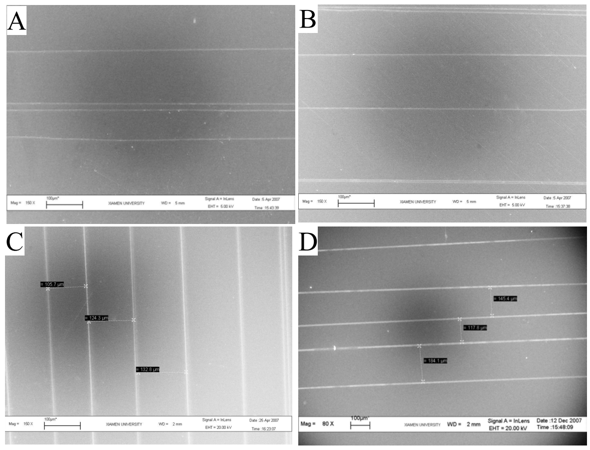


Figure 5 The collector moving speed is 1.6m/s, 2.2m/s, 2.5m/s and 7m/s in A, B, C, D respective. PEO concentration is 20%, the electrode to collector distance is 2mm and applied voltage is 2.3kV.

The effect of different collector moving speed and different electrode to collector distance also studied in this work. The line width of thin film micro structure is increasing with the electrode moving speed as show in Figure 6; electrode moving speed rang from 1m/s to 2.8m/s and thin film line width is various from 1.5μm to 5.2μm, PEO solution concentration 20%, electrode to collector distance 2mm and applied voltage 2.3kV.

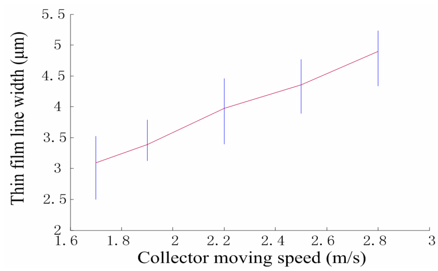


Figure 6 Thin film line width with collector moving speed

Figure 7 shows the relationship between electrode to collector distance and thin film line width, PEO solution concentration is 20%, electrode moving speed is 1.7m/s and 1.9m/s, electrode to collector distance rang from 2mm to 10mm and thin film line width is various from 2.5μm to 3.8μm. The applied voltage is increasing with electrode to collector distance. The relationship between applied voltage and electrode to collector distance is shown in Figure 8. It seems from Figure 8, the relationship between applied voltage and electrode to collector distance is nearly linear.

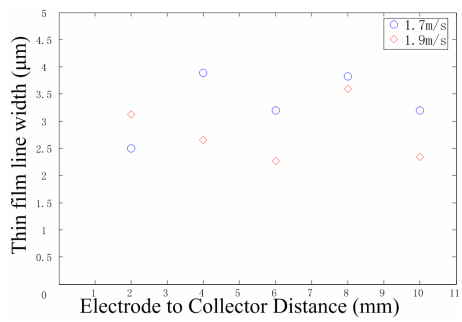


Figure 7 Thin film line width with electrode to collector distance

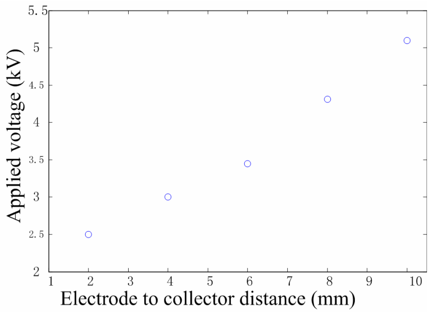


Figure 8 Applied voltage with electrode to collector distance

DW thin film with line width of several micrometers can be drawn on substrate, when needle tube used as spinneret and electrode to collector distance shorted to 2mm~10mm. The surface smoothness, thickness, line width and position deposition can be controlled by optimizing the electrospinning process parameters, such as collector moving speed, solution concentration and electrode to collector distance.

## SUMMARY

The DW technology based on NFES can be employed to fabricate micro/nano-structures for flexible electron. NFES is a new way of controllable electrospinning, a tungsten probe of 25μm tip diameter used as spinneret with shorter electrode to collector distance of 500μm~3000μm and lower applied voltage 600V, nanofiber of 50nm~500nm diameter can be drawn orderly and accurately on the substrate. Micro-structure with line width of several micrometers can be direct-written controllably, when needle tube of 232μm inside diameter used as spinneret with the electrode to collector distance of 2mm~10mm and applied voltage of 2kV~5kV. The line width, accurate position deposition, surface smoothness and thickness of micro-structure can be controlled by optimizing the electrospinning parameters of DW process.

As a new method for flexible electronic manufacturing, micro/nano-structure DW technology has advantages of simpler and more easily controlling process, lower cost and narrower line width. The DW micro/nano-structure is smoother, more continuous and better electronic character, which would satisfy the development require of flexible electron better. DW has open a new way for flexible electronic manufacturing, but much work is needed to make it suitable for the industrial applications.

## ACKNOWLEDGMENT

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