Proceedings of the 1st IEEE International
Conference on Nano/Micro Engineered and Molecular Systems
January 18 - 21, 2006, Zhuhai, China

Electrospun Nanofibers Bundles

Daoheng Sun[1, 2*], Lingyun Wang[1], Dezhi Wu[1], and Liwei Lin[2]

[1]*Department of Mechanical and Electrical Engineering, Xiamen University, China, 361005*
[2] *Berkeley Sensor and Actuator Center*
[2]*Department of Mechanical Engineering, University of California at Berkeley, CA 94720-1740*

***Abstract*—Aligned nanofibers, filament bundle composed of large number of nanofibers have potential applications such as biomaterials, composite materials etc. A series of electrospinning experiment has been conducted to investigate the electrospinning process, through which, some parameters such as polymer solution concentration, bias voltage, distance between spinneret and collector, solution flow rate etc have been setup to do the experiment of nanofibers bundles construction. This work firstly reports electrospun nanofibers bundles through non-uniform electrical field, and nanofibers distributed with different density on electrodes from that between them. Thinner nanofibers bundle with a few numbers of nanofiber is collected for 3 seconds; therefore it's also possible that the addressable single nanofiber could be collected bridging the two electrodes.**

Keywords-Electrospinning; Nanofibers bundles; Density; Non-uniform electrical field

I. INTRODUCTION

Electrospinning based on strong electrostatic driving mechanism can fabricate long and continuous nanofibers with diameters less than 100nm [1, 2], even 5nm [3] and nanotubes [4]. Non-woven mat or aligned fibers have potential applications such as bio-scaffold, wound dressing, filtrations, defense dress and composite materials [2, 17] etc. Another application area could be micro/nano devices such as electronic devices, sensors [5-7], and actuators. Furthermore, it could be feasible to deposit biomaterials such as DNA on chip without thermal damages because the process is conducted at room temperature under atmospheric condition, without the need of lithography or direct contact such as in the Dip-Pen nanolithography setup [8].

Filament bundle composed of large number of nanofibers is a common bio-structure [9]. Artificial aligned nanofibers, nanofibers bundle, and nanofibers mat with controlled density have potential applications such as biomaterials, filtrations, and composite materials [2, 10] etc. Deposition of addressable nanofibers bridging two electrodes is paramount important for micro/nano devices. However, the electrospinning process is chaotic by nature such that it is difficult to control the deposition position and amount of electrospun nanofibers [1, 2]. Limited works regard to aligned nanofibers have emerged during last few years, for example, aligned nanofibers controlled by electrical field [11], and by using rotational mandrel or particular mechanical structure [12] have been reported. This work firstly reports electrospun nanofibers bundles through non-uniform electrical field, and nanofibers distributed with different density on electrodes from that between them.

II. EXPERIMENTS

As one of the most extensively studied polymers for electrospinning, Poly (ethylene oxide) (PEO) has been widely used with/without the addition of another polymer [13]. In this letter, PEO solutions are electrospun in order to investigate the effect of process parameters on electrospinning, such as spinning voltage, solution concentration, the distance between the tip and the collector (ground electrode), and solution flow rate. PEO (M_v =300,000) was purchased from Aldrich, ethanol and deionized water were all reagent grade. The concentration of PEO solution is from 0.5%wt to 7.32%wt PEO in 50 wt %/wt50% water/ethanol solvent.

Two kinds of electrospinning system were setup in which the high voltage power supply is ES30P-10W (Gamma High Voltage Research). The first system for conventional electrospinning is the same as others [14], in which the inside diameter of the needle tip is 300 μm, A copper plate is as the collector which is connected to the ground. The distance (h) from tip to the surface of the collector is 5cm to 13.5cm. The solution flow rate is 0.1~5ml/h which is controlled by the syringe pump (WPI, SP201). The polymer solution is delivered from syringe (BD 3ml) through plastic tubing. In order to electrospin nanofibers bundles, the collector with two electrodes with the shape of saw-like structures is setup, which is depicted in Figure 1, in which the gap between the tips on the collector is 100μm~500μm cut from a copper plate.

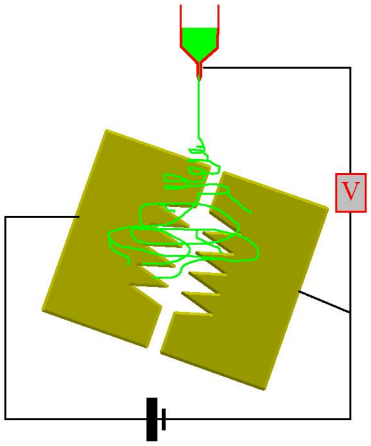

Figure 1 Schematic diagram of the electrospinning setup for nanofibers bundles

This work is supported by National Natural Science Foundation of China and Natural Science Foundation of Fujian Province.
Contact author: **sundh@xmu.edu.cn.*

III. RESULTS

As the first step, conventional electrospinning experiments have been conducted before nanofibers bundles electrospinning in order to understand well the mechanism of electrospinning. Process parameters such as PEO's concentration with 0.5%~7.32%wt, the distance between needle tip and ground (electrode-gap-width) of 5.0cm ~ 13.5cm, bias voltage of 12kV~20kV, and solution flow rate of 0.1 ml/hr to 5ml/hr were considered. Two of SEM microphotos of the electropinning results are shown in Fig. 2.

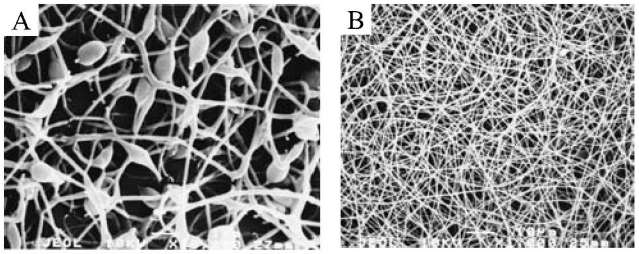

Figure 2 Nanofibers from conventional electrospinning with needle tube's diameter of 300μm. A, 3%PEO, 20kV, 0.5ml/h, electro-gap-width: 11cm; B, 7.32%PEO, 12kV, 0.5ml/h, electro-gap-width: 11cm.

Polymer solution concentration is one of the most important roles played in the electrospinning process. Experiments show that PEO with concentration lower that 2%wt cannot be electrospun into nanofibers under the electrode-gap-width of 10 cm, only PEO droplets and film are electrosprayed on the substrate because of the lower viscosity. With concentration higher than 2%wt, PEO nannofibers can be collected on the substrate, Figure 2A, B. For 3%wt or lower, a lot of defects exist, such as bulk polymer, beads (Fig.2A), thicker fiber with diameter of several microns, split fibers etc. PEO with 5%wt and 7.32%wt were also investigated, defect free nanofibers with round cross section were electrospun. The result, which the higher the concentration of the polymer solution, the thicker the nanofibers, is agreement with the work of [13].

Enough electrode-gap-width is necessary so that (1) the solvent can be evaporated as much as possible before the fibers arrive to the collector, and (2) the fibers get to be thinner because of solvent evaporation, whipping and splitting. Take the 3%wt PEO as an example, if the electrode-gap-width is shorter than 5cm, long continuous nanofibers couldn't be electrospun [15]. There are two parts between the electro-gap-width [1, 2], the first one is the liquid jet with diameter of several microns, and the second one is the area of whipping and splitting which makes the fibers thinner. If we collect the fibers in the first region by using a moving collector, we can get wet microfibers or microlines, otherwise, we can collect random non-woven nanofibers (Fig. 2A, B).

According to our observation during the electrospinning, bias voltage affects the nanofibers' diameter, the length of the liquid jet, the numbers of the jet on the droplet surface, and the jet speed, if the electrode-gap-width, shape of the two electrodes is fixed. The effect of bias voltage on the nanfibers' diameter agrees with other researchers [13]. Higher bias voltage shortens the length of the jet line, so the whipping and splitting happen earlier which results in the nanofibers' chaotic motion to larger extent [16]. The other interesting phenomenon is that multi-jet is generated from the droplet in the front of the needle tip under higher bias voltage. The reason should be because of increasing of the charge density on the droplet surface. The relations between the numbers of jet and the bias voltage or charge density will be explored in the future. The droplet becomes smaller, and finally disappears under higher bias voltage and fixed solution flow rate.

Wide range of solution flow rate variation is permitted. Liquid jet can observed when flow rate with 0.1ml/hr to 5ml/hr is used. But, the pendant droplet size increases with the solution flow rate, and then the possibility of the multi-jet generation become larger. With lower flow rate, the pendant droplet disappears and the jet is generated from the sidewall of the tube.

However, the electrospinning process is chaotic by nature such that it is difficult to control the deposition position and the alignment direction [1, 2]. This work firstly reports electrospun nanofibers bundles through non-uniform electrical field, and nanofibers distributed with different density on electrodes from that between them. In Figure 1, the collector has two electrodes with sharp tips and a parallel side conterpart so that we can investigate the effects of non-uniform electrical field on the nanofibers structure.

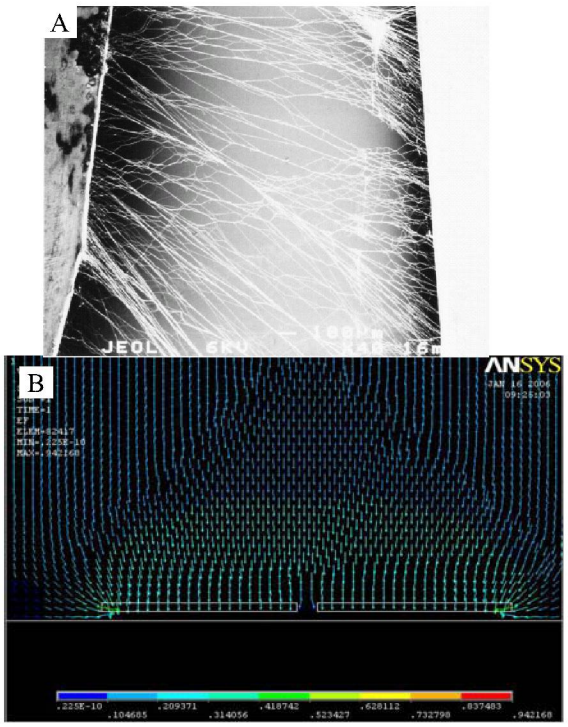

Figure 3 A, Aligned nanofibers between electrodes. The electrospinning voltage (between spinneret and collector) is 12kV, with electrode-to-collector distance of 11cm. Applied voltage on the two collector electrodes (copper) is 150V, Collection time: 30s; the polymer solution used is 7.32%PEO. B, Electrical field simulation Gap: 100μm; the distance of spinneret to collector: 10cm, bias voltage of 10kV; Applied voltage between two collector electrodes: 0V.

The electrode geometry on the collector plays important role on the nanfibers distribution. Figure 3A shows that the nanofibers are collected on the collector that has two parallel electrodes with gap of 1mm around. The nanofibers without bundles are aligned between the two parallel electrodes, which is consistence with [1].

From the simulation result (in Figure 3B) of the electrical field between the spinneret and the collector with two parallel electrodes, it can be seen that the direction of the electrical force line between the two parallel electrodes is different from other area which is perpendicular to the electrode edge such that the nanofibers with charges are stretched to two electrodes during their dropping down to the collector.

On the vertex of the electrodes shown in Figure 4, the nanofibers tend to congregate to form a bundle with the direction of perpendicular to the edge, because the electrical field gradient is much larger than other area. A collector has two electrodes with sharp tips is used to investigate the phenomena in detail. The gap width between the counterpart tips is from 50μm to 500μm, and the applied voltage is from 0 Volts to 150Volts.

Figure 4 Nanofibers bundles at the vertex of the collector. The electrospinning voltage (between spinneret and collector) is 12kV, with electrode-to-collector distance of 11cm. Collection time: 30s; The polymer solution used is 7.32%PEO.

All the three pairs of copper tip are bridged by electrospun nanofibers bundles at the applied voltage of 0V to 150 V. In Figure 5A, the electrospinning voltage (between spinneret and collector) is 12kV, with spinneret-to-collector distance of 11cm, the voltage applied between the two electrodes (copper) with saw-like shape is 150V, and the collection time is 30s. Straight nanofibers bundle with length of 500μm and width of 10μm constructed between two electrodes with sharp tip is demonstrated in Figure 5B. It is shown from Figure 5B and C that nanofibers bundle between the electrodes with gap of 50μm (Figure 5C) is different from that of 500μm (Figure 5B). For the tips with gap of 500μm, the nanofibers in the bundle are aligned, which has more ordered structure, however, for the tips with gap of 50μm, some nanofibers in the bundle appear to be the radiation structure from the tip. This means nanofibers bundle structure maybe affected by the electrode-gap that determines the electrical field between the two electrodes.

Simulation result is shown in Figure 6, in which the gap between the tips is 100μm and applied voltage is 100V (100V on left tip, and the right one grounded). The distance of the spinneret to collector is 10cm, and the bias voltage is 10kV. The electrical field in the area around grounded electrode is much higher, which attracts the nanofibers to the right tip, and causes the disorder of the nanofibers distribution on the electrode.

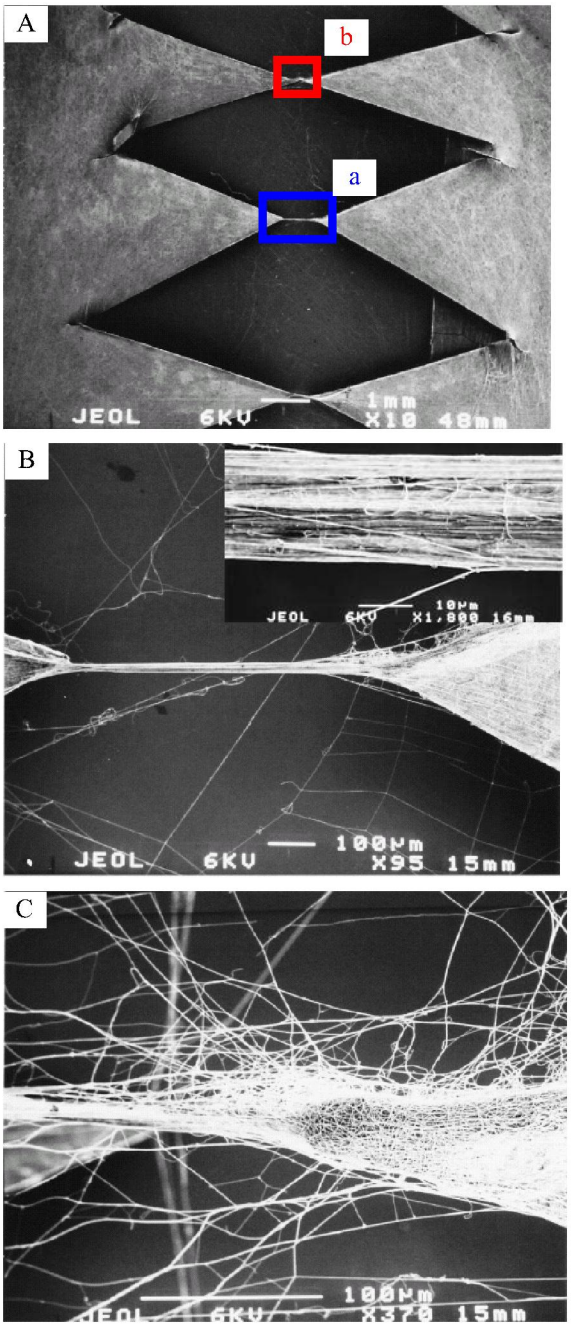

Figure 5 Nanofibers bundles between tips induced by non-uniform electrical field. A, Overview of the nanofibers bundles bridging tips; B, Enlarge picture of the bundle at site (a) in A, which is with a gap of 500μm between the tips, inset is the amplification of the bundle structure; C, Enlarge picture of the bundle at the site (b) in A, with gap of 50μm between the tips. The electrospinning voltage (between spinneret and collector) is 12kV, with electrode-to-collector distance of 11cm. Applied voltage the two collector electrodes (copper): 150V, Collection time: 30s; The polymer solution used is 7.32%PEO.

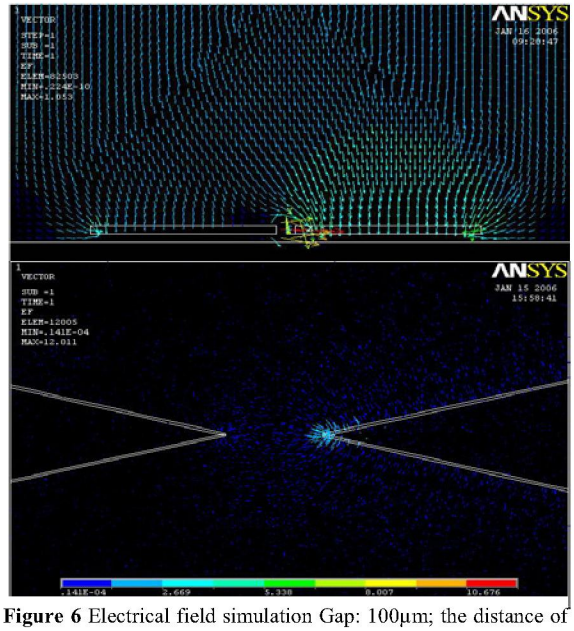

Figure 6 Electrical field simulation Gap: 100μm; the distance of spinneret to collector: 10cm, bias voltage of 10kV; Applied voltage between two collector electrodes: 100V.

Thinner nanofibers bundle with a few numbers of nanofiber is collected for 3 seconds (Figure 7), therefore it's possible that the addressable single nanofiber could be collected bridging the two electrodes.

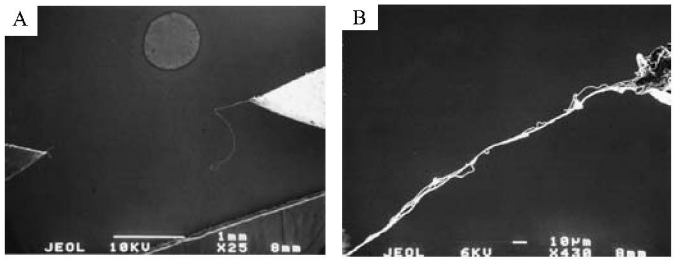

Figure 7 Nanofibers bundles composed of a few numbers of nanofiber bridging electrodes. The electrospinning condition is the same as in Figure 2, but with collection time 3s. A, a broken nanofibers bundle; B, enlarge view of the bundle with 3~5 nanofibers

The nanofibers density on electrode is much larger than that between electrodes except for the area between the tips (Figure 5B, C). It's more obvious from Figure 8 that the nanofibers are concentrated on the tip area which has higher electrical field strength shown in Figure 6. Therefore we can envision that the distributed nanofibers density on collector can be controlled through patterned electrodes.

IV. Conclusions

This work firstly reports electrospun nanofibers bundles construction through non-uniform electrical field, and nanofibers distributed with different density on electrodes from that between them. Straight nanofibers bundle with length of 500μm and width of 10μm is constructed between two electrodes with sharp tip. It is shown that nanofibers bundle structure can be affected by the electrode-gap that determines the electrical field between the two electrodes. Thinner nanofibers bundle with a few numbers of nanofiber is collected for 3 seconds; therefore it's possible that the addressable single nanofiber could be collected bridging the two electrodes. The nanofibers density on electrode is much larger than that between electrodes except for the area between the tips, so the distributed nanofibers density on collector can be controlled through patterned electrodes

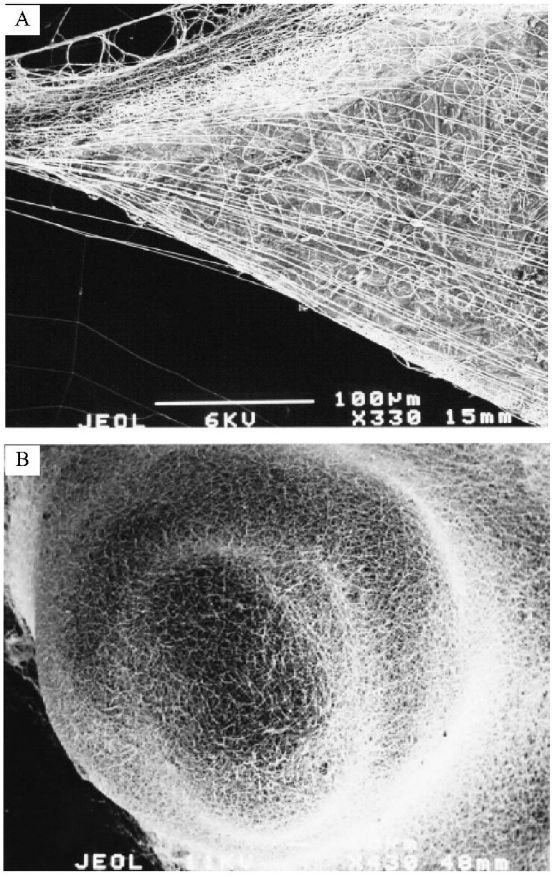

Figure 8 Higher density of nanofibers on the grounded electrodes (right side tips shown in Figure 5A) than other area induced by non-uniform electrical field. A, alignment-like nanofibers on the tip, with a gap of 500μm, applied voltage of 150V; B, round thick nanofibers mat on the tip, with gap of 50μm, applied voltage of 150V. The electrospinning process parameters are the same as in Figure 5.

Acknowledgment

This work is also supported by Berkerly Scholarship Program. The authors thank Evan Stateler, Robert Hamilton (Micro Lab. UC Berkeley) for their high voltage power supply, and Ron Wilson for his nice SEM works.

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