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Description	

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Fabrication of a submicron patterned electrode using an electrospun single fiber as a shadow-mask

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ABSTRACT

We realize a uniform submicron-gap electrode by using an electrospun single fiber as a shadow-mask. By stretching an electrospun fiber, we can decrease the diameter of the fiber from 2 μm to 564 nm with its standard deviation of 57.7 nm. We place the fiber on the center of a Si/SiO_2 substrate followed by the deposition a molybdenum trioxide adhesion layer and Au electrode. After removing the fiber from the Si/SiO_2 substrate, the submicron-gap gold electrode is formed. Characterization of the gap with scanning electron microscope revealed that the gap has a good uniformity; the average gap length is 865 nm throughout 2mm gap width.

Keywords
Electrospinning, Submicron-gap patterned electrode, Single fiber, Shadow-mask

1. Introduction

Recent years, the intensive studies have developed the electronics using the organic semiconductor. In particular, organic filed effect transistor (OFET) is the promising device, since the transistor is the essential element for realizing flexible electronics. However, due to the poor mobility of the organic semiconductor, the channel length of the OFET is needed to be decreased for the fast operation. Thus, the development of techniques to fabricate the narrow gap electrode is attractive to date. To fabricate submicron-gap electrodes, various techniques have been developed including photolithography, electron beam (EB) lithography [1], nanoimprinting [2], atomic force microscopy (AFM) lithography [3], self-aligned printing [4]. In order to realize the low-cost advantages of organic electronics, the patterning process of the electrode should be simple, low-cost, and effective for material use. Therefore, it is essential to develop the simple and cost effective electrode patterning process.

Electrospinning is a simple and cost effective method of producing polymeric fibers with diameters ranging from a few micrometers to nanometers and this method has been attracted much attention in the past decade [5]. However, only a few literatures have reported on the characteristics of an electrospun single fiber since preparing a single fiber with electrospinning method requires skillful fabrication technique [6-7]. Recently, we have developed a simple method to prepare an aligned single fiber by using the alternative switching electrospinning technique [8-9]. The advantages of our method are twofold. It allows to precisely controlling; (1) the number of fibers by switching times between two collector electrodes and (2) a diameter of a single fiber by post stretching process.

In this work, we developed a simple and a low-cost technique for fabricating submicron-gap patterned electrodes using the electrospun single fiber as a shadow mask. By taking advantage of the features in our method, we can control an average size and uniformity of the diameter of a single fiber by post-stretching. We evaluated the uniformity of the fiber diameter as a function of stretching ratios. Then, we fabricated patterned submicron-gap electrodes using the well-characterized single fiber as a shadow mask. Characterization of the gap with scanning electron microscope reveals that the gap has a good uniformity.

2. Experimental

Poly(ethylene oxide) (PEO, *Mv* = 400,000, Aldrich) was used to fabricate an electrospun single fiber-mask. PEO was dissolved in chloroform with a concentration of 30 mg/ml. The solution was then loaded to a glass syringe equipped with a stainless steel needle (0.3 mm in diameter). The solution was continuously supplied using a syringe pump at a rate of 0.5 ml/h. The needle was connected to a high-voltage power supply (CN-30-MHVP, Matsusada Precision Inc.). The distance between the needle and collectors, composed of two pieces of stainless steel, was 17 cm and the voltage applied to the needle was 3.0 kV. Details on the fabrication of number-controlled aligned fibers are given elsewhere [8]. Briefly, one of two collectors were applied with a negative voltage (-500 V) while another collector was either grounded or applied positive voltage (Fig. 1, STEP1). The negatively biased electrode was switched alternatively by a mechanical switch. Depending on switching times, number-controlled aligned fibers were formed bridging between the two collectors. Then, the certain numbers of the fiber were mechanically stretched in order to control the diameter of the fiber (Fig. 1, STEP2).

An electrospun single fiber was carefully placed on a center of Si/SiO_2 substrate (25 mm × 25 mm) pre-treated with HMDS (Fig. 1, STEP3). The thickness of the SiO_2 dielectric layer was 400 nm. Then, a 2 nm-thick molybdenum trioxide (MoO_3) adhesion layer and a 28-nm thick Au were deposited on the substrate (Fig. 1, STEP4) through a metal mask with a rectangular-shape aperture (2 mm × 10 mm), which defines the size of electrodes. Removing a single fiber by dissolving with chloroform formed a patterned electrode separated by a gap defined by the diameter of the fiber (Fig. 1, STEP5).

To determine the average diameter in a single fiber, scanning electron microscope (SEM) images were measured with a HITACHI S-4500 SEM. We randomly measured 100 of SEM images and used for calculating the average diameter of the single fiber. On the other hand, the average diameter among 100 fibers was determined from the SEM images taken from 100 different fibers. To characterize the uniformity of the single fiber-mask, we also calculated standard deviation from the 100 SEM images. For the characterization of a uniformity of a gap length in a patterned electrode, we measured 150 SEM images along the 2-mm electrode gap width. The average length and the standard deviation of the gap in the patterned electrode were determined by the analysis of the SEM images.

3. Results and discussion

A single submicron fiber was prepared by the alternative switching electrospinning method followed by post stretching. Figure 2 shows SEM images of the electrospun single fiber stretched 41 times. This fiber exhibits very high aspect ratio more than 3.6×10^5 (i.e., the average fiber diameter was 564 nm and the total fiber length was 205 mm.). Figure 3a shows average diameters in a single fiber as a function of stretching ratio. As increasing in stretching ratio, the average diameters of the single fiber decreased from 2 μm to 564 nm. Inset in Fig. 3a shows the average diameters among different 100 fibers. In both cases, the fiber diameters were saturated in a high stretched region (stretched 15 – 41 times). This saturation would be due to that the fiber density reached to the critical density.

Figure 3b shows standard deviations of fiber diameters measured in the single fiber and among 100 fibers (inset) as a function of stretching ratio. The standard deviations decreased from 139 nm to 57.7 nm (about 40 % reductions) by stretching the single fiber up to 41 times. Similar improvement of the uniformity was also observed in 100 fibers. These results suggest that stretching process effectively improves the uniformity of both the diameter of the single fiber and in multiple fibers. On the other hand, we observed the drastic increase of the standard deviations of fiber diameters at the stretching ratio of 2 times and 3.6 times. Figure 4 shows SEM images of electrospun fibers with different stretching ratios. Unstretched fibers exhibit the inhomogeneous fiber diameter (Fig. 4a). As clearly seen in Fig. 4b, beads are formed in the fibers at the initial stage (stretching ratio is 2). The bead formation was come from "necking" of a fiber and causes the increase in the standard deviation in Fig. 3b. The necking mechanism during bead formation can be described as follows. In unstretched fibers, since the fiber diameter was not uniform, some part of the fiber with smaller cross-sectional area will be subject to higher stress than the rest, due to the stress concentrations [10]. After the cross-section of necks reached to minimum area, called neck stabilization, the larger cross-sectional parts of the fiber started extending [11]. As a result, beads were generated in a fiber at the initial stage of stretching process. Finally, the beads were disappeared when all part of the fiber reached to the minimum cross-sectional area, i.e. critical density. (Fig. 4d)

By using a highly stretched (stretching ratio = 41) single fiber as a shadow-mask, we fabricated submicron-gap electrodes on a Si/SiO_2 substrate (Fig. 5). The average gap length and the channel width of the pattered electrode were 865 nm and 2 mm. Figures 6a and 6b show the histograms of the diameters of the stretched fiber mask and of the gap lengths of the patterned electrode measured in the entire channel width (2 mm). The standard deviation of the gap lengths was 109 nm, which is 12.6 % of the average gap length. This standard deviation of the gap length demonstrate excellent uniformity in our method since the standard deviation was evaluated in a very large region (2 mm) compared with the size of the gap length. When we reduce the measurement region down to 10 μm, the standard deviation was further improved to 22 nm. The average gap length (865 nm) of the patterned electrode was larger than the average diameter (564 nm) of the single fiber-mask. This broadening would be caused during the fabrication processes of the electrode such as shadowing effect during the metal deposition and/or lift-off process of the fiber mask. Since we fixed the substrate during the evaporation of the layers of MoO_3 and Au, rotation of the substrate may further reduce the average gap of the patterned electrode [12]. Another possible explanation would be the leyers of MoO_3/Au were peeled off during the lift-off process of the fiber-mask. Figures 7a and 7b show the histgrams of deviation ratios (DR) of the diameters of a stretched fiber-mask and the gap lengths of a patterned electrode fabricated with a single fiber-mask. To directly compare the uniformity of the fiber-mask and the resulting gap length, we used a deviation ratio calculated by $DR = D/A \times 100$. Where DR is deviation ratio (%), D is the deviation of fiber diameters or gap lengths, and A

is the average diameter or gap length. The histograms of deviation ratios show almost similar shape, which means that uniformity of the gap is mainly derived from that of the fiber-mask and the distribution of the gap length was reproduced form that of the fiber-mask.

4. Conclusions

In summary, we have demonstrated the simple and low-cost technique for fabricating submicron-gap patterned electrodes with good uniformity using the electrospun single fiber as a shadow mask. A single fiber was prepared by our alternative switching electrospinning method and post stretching of a single fiber decreased the average diameters of the fiber from 2 μm to 564 nm, and the standard deviation of the fiber diameter decreases from 139 nm to 57.7 nm as well. By using a single fiber as a shadow-mask, we fabricated a submicron-gap electrode pattern with the average gap length of 865 nm throughout 2 mm electrode width.

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LIST OF FIGURE CAPTIONS

Fig. 1. Schematic illustration of our method to fabricate submicron-gap electrode. In STEP1 we produce a single fiber-mask by switching the negatively biased electrode once. In STEP2 the single fiber-mask is stretched to reduce the diameter and improve the diameter uniformity. In STEP3 the fiber-mask is put on a Si/SiO2 substrate. In STEP4 metallic electrode is deposited. In STEP5 the fiber-mask is removed by dipping into chloroform, and a submicron patterned electrode is obtained.

Fig. 2. SEM images of an electrospun single fiber-mask after stretching to 41 times. The scale bars are 10 μm and 1 μm for the inset.

Fig. 3. (a) Fiber diameter and (b) standard deviation of a single fiber-mask as a function of stretching ratio. Insets show fiber diameter and standard deviation of 100 fiber-mask as a function of stretching ratio.

Fig. 4. SEM images of fiber-masks with different stretching ratios; the stretching ratios are; (a) unstretched, (b) 2, (c) 5, and (d) 11. The scale bars are 30 μm.

Fig. 5. Images of (a) SEM and (b) AFM of a patterned electrode. The scale bar in SEM image is 10 μm. The inset in 4(b) shows enlarged SEM image of a patterned electrode (scale bar is 750 nm).

Fig. 6. Histograms of (a) the diameters of a stretched fiber-mask (stretching ratio = 41), and (b) gap lengths of a patterned electrode fabricated with a fiber-mask.

Fig. 7. Histograms of deviation ratios of (a) the diameters of a stretched fiber-mask (stretching ratio = 41), and (b) gap lengths of a patterned electrode fabricated with a fiber-mask.

Fig. 1

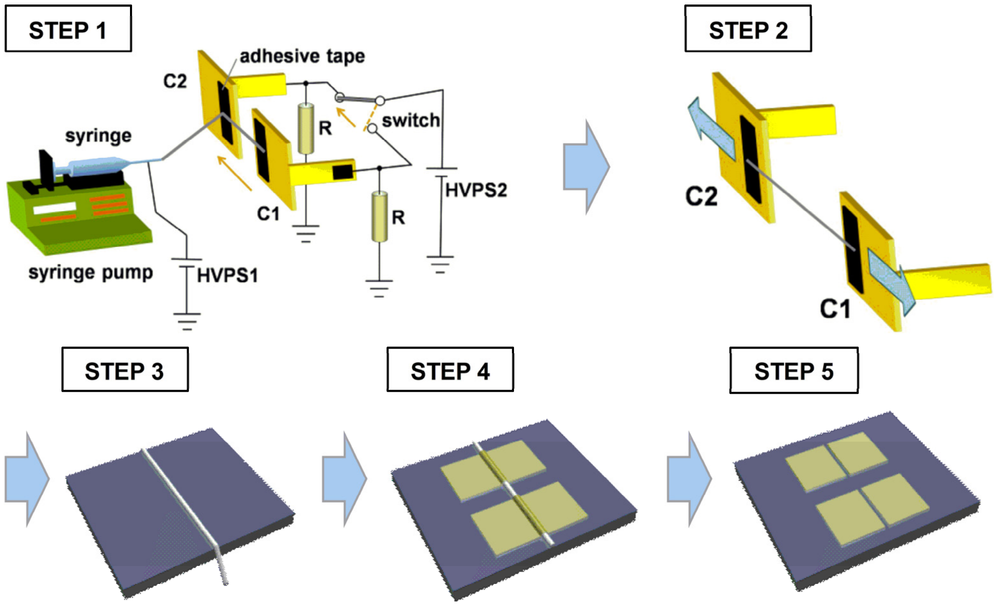

STEP 1
adhesive tape
C2
syringe
R
switch
C1
HVPS2
R
syringe pump
HVPS1
STEP 2
C2
C1
STEP 3
STEP 4
STEP 5

Fig. 2

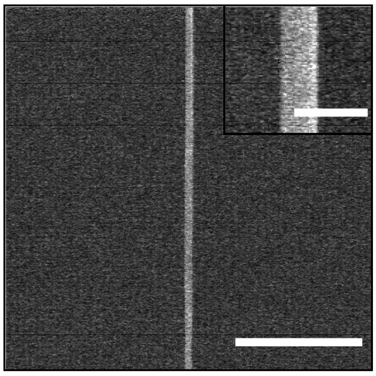


Fig. 3

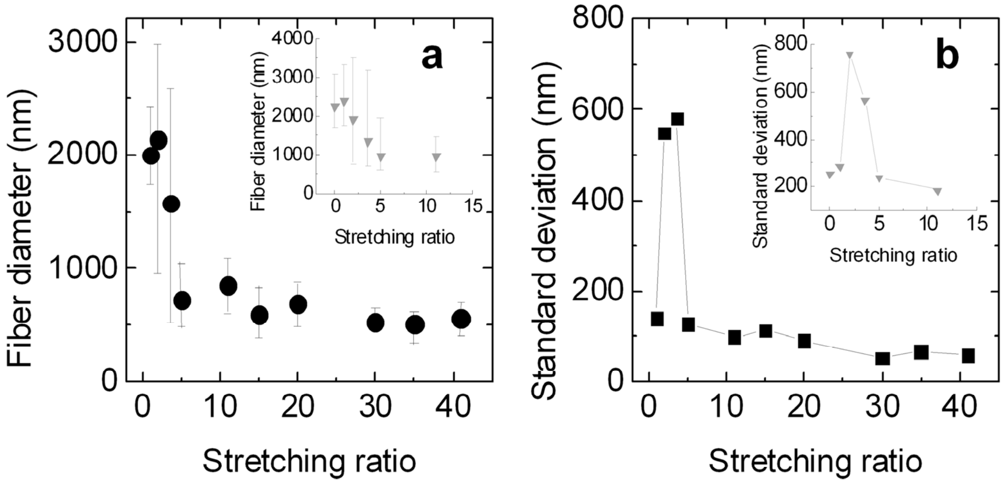

a
Fiber diameter (nm)
Stretching ratio
b
Standard deviation (nm)
Stretching ratio

Fig. 4

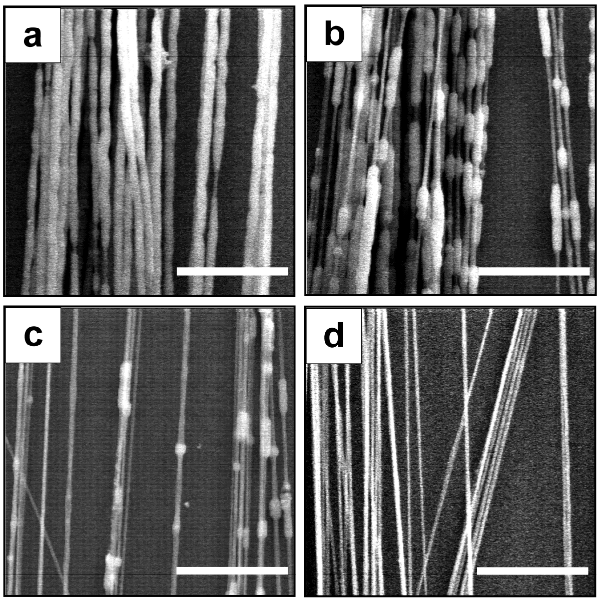


Fig. 5

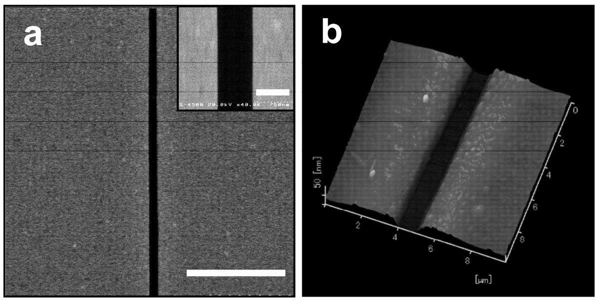


Fig. 6

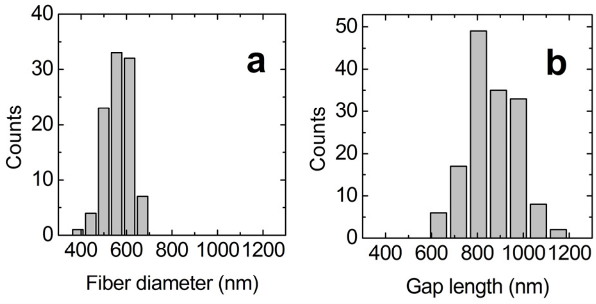
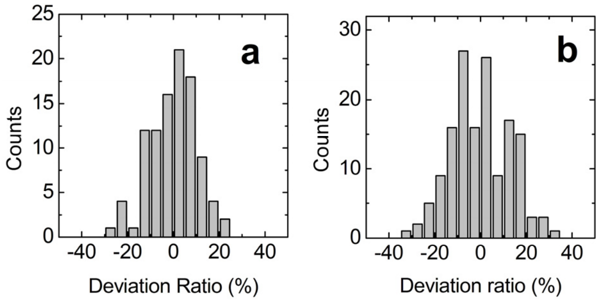

a
Counts
0
10
20
30
40
400
600
800
1000
1200
Fiber diameter (nm)
b
Counts
0
10
20
30
40
50
400
600
800
1000
1200
Gap length (nm)

Fig. 7


a
b
Counts
Deviation Ratio (%)
Deviation ratio (%)
0
5
10
15
20
25
30
-40
-20
40