# CHIP-TO-CHIP FLUIDIC CONNECTORS VIA NEAR-FIELD ELECTROSPINNING

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# ABSTRACT

Site-specific, chip-to-chip fluidic connectors have been demonstrated via near-field electrospinning (NFES) in a fashion similar to the wire bonding technique in IC manufacturing. Electrospun polymer fibers function as the sacrificial material with deposition control better than 10µm in the planar direction to connect two separated chips. A coating process and sacrificial layer etching process are followed to make micro/nano fluidic channels of 50nm~5µm in inner diameter. Preliminary parameter and flow characterizations have been conducted. As such, this fabrication/packaging technology could enable on-chip and off-chip fluidic transportations and networks in MEMS applications, including BioMEMS and microfluidics.

## **INTRODUCTION**

Fluidic interconnectors have been a bottleneck in developing micro/nano fluidic systems. Previously, various methods such as polymer sealant [1], epoxy [2], and rubber O-rings [3] have been used to make micro-to-macro connectors. However, state-of-the-art technology is typically limited to manual operation by using capillary tubes as the connectors and epoxy or mechanical fixture to secure the terminals.

Electrically driven polymer jets and their applications have been intensively studied in recent years. In spite of its feasibility to construct fine polymer fibers, conventional electrospinning is uncontrollable, as the electrically driven liquid jets are chaotic in nature [4]. Previously, a near-field electrospinning (NFES) has been demonstrated [5]. It has the capability to control the deposition location of polymer fibers in contrast to the random deposition of conventional electrospinning. This work presents and demonstrates that "wire bonding" type fluidic connectors are possible for micro/nano fluidic systems by using NFES.

Figure 1 shows: (a) the concept of "wire bonding" type fluidic connectors; (b) the operation principle of the NFES process; and (c) an experimental demonstration of NFES including a Taylor cone and jet initiation [5]. In the operation of NFES, a polymer solution attached to the tip of a tungsten electrode is electrically driven toward a collector that is placed in distance of about 500-1000µm away from the electrode. Once the electrical force overcomes the surface tension of the solution, a polymer jet is ejected

from the apex of a Taylor cone [6, 7] to produce location controllable solid fibers on the collector. Accelerated in high electric field, the final jet speed near the collector is up to 20cm/s; that is, a polymer fiber pattern can be produced on a collector at a speed of 20cm/s for fast automation processes.

Previously, various methodologies have been demonstrated to make micro/nano fluidic channels based on nanofibers. For example, hollow nanofibers can be fabricated directly from the electrospinning process by a co-electrospinning setup [8, 9]. Micro or nano channels can also be made by indirect method using nanofiber as the sacrificial layer. In this category, rotational mechanical mandrel has been used to make controllable electrospun nanofibers and channels [10] and AFM mechanical drawing has been applied to make local fluidic networks [11].





Figure 1. (a) The concept of "wire bonding" type fluidic connectors for input/output and chip-to-chip connections; (b) operation principle of near-field electrospinning; and (c) experimental result showing Taylor cone and polymer jet [5].

In this work, by moving the collector using a Newport XPS x-y stage nanocontroller, polymer fibers of 50nm~ $5\mu$ m can be orderly deposited on the collector for desirable patterns with location controllability of better than 10 $\mu$ m. Figure 2 shows two demonstrations

including, (a) the deposition of "Cal" in an area of  $1.0 \text{ mm} \times 0.5 \text{ mm}$  where the diameter of the fiber is 170nm, and (b) continuous production of well-aligned nanofibers on top of a  $1.5 \text{ cm} \times 1.5 \text{ cm}$  silicon chip.



Figure 2. Experimental demonstrations showing the control of near-field electrospinning: (a) "Cal" is drawn in an area of 1.0mm x 0.5mm; (b) well-aligned fibers on a 1.5cm x 1.5cm chip.



Figure 3. Fabrication process of chip-to-chip fluidic interconnectors.

## FABRICATION PROCESS

NFES is applied to construct chip-to-chip fluidic connectors and the process is illustrated in Figure 3. First, a polymer fiber functioning as sacrificial material is electrospun from one silicon chip to another to construct micro/nano connector. The writing speed is fast enough for fibers to go across the gap between two chips. At low writing speed, fibers are accumulated at the deposition spot such that it is possible to control and slow down the movement at the beginning and end in making the connector to deposit extra fibers as illustrated for fluidic input/output ports. Experimentally, we used PEO (polyethylene oxide) as the sacrificial fiber material due to its good solubility in water and other organic solvents [12].

A thin layer material for inner surface modification is deposited, if needed, on the surfaces

(top and bottom) of the fiber to construct possible hydrophilic inner surface of fluidic channels. In the prototype demonstration, we chose to deposit a 5nmthick sputtered gold-palladium layer in this step. Afterwards, a conformal deposition of channel material is followed. Two material systems that can be conformally deposited at room temperature have been tested: PECVD (Plasma Enhanced Chemical Vapor Deposition) silicon oxide and Parylene. Parylene is flexible as well as impermeable for most fluids but is hydrophobic such that an internal hydrophilic coating is necessary. Silicon oxide is brittle but hydrophilic such that no hydrophilic coating is needed. In the final step, the sacrificial polymer fiber is selectively etched away either by soaked in hot water of 80°C for 2 hours or baked at 200°C for 2 hours. It is estimated that the water etching process can penetrate about 5mm into the channel and there is no length limitation for the baking process.

#### **EXPERIMENTS, RESULTS AND DISCUSSIONS**

Figure 4 shows the SEM picture of a fabricated example that includes three fluidic channels going across two silicon chips separated 0.5mm apart. Experimentally, we found that when the height from the collector to the electrospinning electrode tip, h, was 0.5mm, the electrospun fibers could connect two chips up to 1.5mm apart. Figure 5 shows SEM pictures of the cross-sectional views of both on-chip and overhanging fluidic channels. The circular-segment shaped channel in Fig. 5(a) is constructed on a silicon substrate. Due to short distance between the electrode tip and the substrate, a polymer fiber by NFES is not fully solidified when it reaches the silicon substrate. Therefore, the cross-section of NFES fiber is not perfectly circular. The nominal fiber diameter is 1µm at the bottom and the height is 0.4µm. The conformal SiO<sub>2</sub> layer by room-temperature PECVD is 0.4µm as the wall thickness.



**Figure 4.** SEM microphoto showing three fluidic connectors (channels) of about  $1.5\mu m$  in diameter connecting two chips that are placed 0.5mm apart.



**Figure 5**. SEM images of cross-sectional views of nanochannels. (a) silicon oxide nanochannel on silicon substrate, (b) a suspended silicon oxide nanochannel, (c) parylene nanochannel on silicon substrate.

Figure 5(b) shows the cross sectional view of an overhanging channel with a nearly circular crosssection with inner diameter of  $0.4\mu m$ . The ECR PECVD is not as conformal as expected as the conformal deposition is affected by deposition conditions, such as shape, aspect ratio or proximity of nearby structures. In this case, this channel is suspended and has thinner wall at the bottom toward the substrate. The deposition thickness was 1 $\mu m$ .

Parylene-based channels are also constructed and one example is shown in Figure 5(c). In order to take the cross-sectional photo of Parylene, the sample is dipped in liquid nitrogen to freeze the flexible Parylene structure and then it is immediately cleaved [13]. PEO fiber under Parylene is removed by water instead of baking since high temperature process may degrade Parylene. Although the solubility is reported enormously high in water [12], the high molecular weight PEO can form a gel-like layer at the interface and obstruct further dissolution inside the fluidic channel. One approach is to utilize the temperaturesolubility dependency of PEO. In hot water, the solubility reduces such that individual particles of polymer can be well dispersed without forming obstacle layers [12]. Experimentally, a temperature of 80°C has been used in the tests and this setup has dramatically improved the etching results. However, it still takes a great deal of processing time to etch through the long channel. It is estimated that a total time of two hours is necessary to etch through a channel of 5mm in length.

The fabricated oxide channels have gone through initial test and Figure 6 shows the time-lapse photos of water movement in a microchannel of  $1.3\mu$ m in width. The cross-section shape is illustrated in Figure 5(a). Because of hydrophilic inner surface, water can easily pass through the channel without any additional driving forces. In this figure, water comes from an open hole which is about 3mm away at the right side. The flow speed is estimated as  $20\mu$ m/s initially.

It is desirable to control the size of these channels. For example, wall thickness is controlled by the channel material deposition process. Inner diameter of the channel is determined by electrospinning process and there are many processing factors such as electrical field strength, viscosity of the polymer solution, and environmental conditions among others [14-16]. Figure 7 shows experimental results on the diameter of polymer fiber with respect to applied voltage and the distance between the electrode tip and the collector. Under the same distance, higher voltage makes larger fiber as expected because higher electric field causes higher liquid flow rate [17]. PEO concentration dependency of polymer fiber diameter is also studied as illustrated in Figure 8. In general, higher polymer concentration can lead to thicker fiber deposition but this phenomenon is not clearly identifiable in the range of tested PEO concentrations.



**Figure 6.** Time-lapse photos showing liquid moving process in a 1.3µm diameter oxide channel.



**Figure 7.** Fiber diameter versus applied voltage of two different tip-to-collector distances. High electrical field leads to larger diameter.



Diameter vs. Applied Voltage under 0.5 mm Height

**Figure 8.** Fiber diameter versus applied voltage of various PEO concentrations. No clear differences between the range of 4-9% PEO concentration.

#### CONCLUSIONS

A chip-to-chip fluidic interconnector process has been suggested to make suspended fluidic channels based on the near-field electrospinning process. NFES is able to produce micro/nano polymer patterns at a speed of 20cm/s, with location controllability better than 10µm. As such, the operation of making fluidic interconnector could be automatically programmed similar to the wire-bonding technology widely used in microelectronics. In the preliminary demonstrations, fluidic channels of 150nm~2µm in diameter have been fabricated and examined using the proposed process. Capillary force was able to drive liquid inside the oxide channels due to their hydrophilic surface nature with initial flow speed of 20µm/s. The diameter of electrospun fibers has also been characterized and it is found that higher electrical field produced larger fiber while PEO concentration does not significantly affect the fiber diameter in 4~9% range.

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