Recycled-paper Platform for Active Microfluidic Chip with Inkjet-printing Carbon Nanotube Ink

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ABSTRACT

Recycled-paper, as a platform substrate of active microfluidic chip, has been explored by incorporating the inkjet-printing carbon nanotube ink for electrode patterning. Overwhelming the presumed disadvantages such as high roughness and conductive containnation by the carbon black ink resided on the surface of recycled papers, our home-made carbon nanotube ink deposited by a ink-jet printer was coated uniformly with a high resolution. The patterns was used as a pattened array of electrode rail for active paper microfluidic devices for transporting a micro-voulume of drops by the electrowetting force.

Keywords: recyled paper, electrowetting, active microfluidic chip, inkjet printing, carbon nanotube ink

1 INTRODUCTION

Since paper was introduced as a microfluidic platform first by Whiteside group [1], the paper-based microfluidic chips (denoted as p-chips) have been devleoped as a passive form such that it utilizes the capillary action to wick a flow of liquid sample likewise Litmus, chromatographic and urine test paper. While the previous researches on the p-chips have, however, focused on the manipulation of the continuous flow confined in the channels in order to utilize only the passive capillary force of paper itself [2-4]; for the surface or inter-structural treatment for patterning the channels, the conventional chips have employed commonly only one selective way relying on the conversion of from hydrophilic paper to hydrophobic or vice versa, and transported a flow of sample through the hydrophilic patterned channels that are isolated by the hydrophobic walls. The source of actuation force for the flow of liquid sample is the competition of attractive and repulsive capillary forces. These passive chips, therefore, have two operational features: (a) transporting the liquid sample in a flow form, mostly by means of capillary force of cellulose fibers consisted of paper and (b) making reactions of liquid sample only at the end of patterned channels on where the chemical regents were pre-immobilized for detecting or analysing probes after the wicked sample arrived [5]. It means that making reaction is so slow due to the weak capillary wicking power to transport the fluidic sample, yet there is no attempt to transport liquid drops actively by using the external power sources [2-4].

Very recently we have introduced a novel microfluidic chip based on paper platform on which the movement of a single digitalized drop or a group of drops actively by switching the electric potential. The speed of movement is so fast that the reaction can complete in a few second unlike minute order for the passive chip. Additionally, the active chip can be controlled in the programmable way in such a way that we transport a group of digitalized micro drops individually and make them reacted along addressable positions on planar platform by applying external electric potential, so called electrowetting technique [6]. Such a powered p-chip, denoted as *the active p-chip*, is the open type without a cover plate. These two features, digital and open, enable us to make it easy the physical and chemical reactions actively on the paper substrate.

The most noticeable difference between active and passive paper-based microfluidic devices is the existence of a patterned array of electrodes on the top paper surface so that the surface tension on the paper substrate can be tuned actively by applying the external voltage. Basic principle of actuating drops on paper is adjusting the surface tension between a drop and an electrode coated on the surface by electric fields. [7]

Here we will introduce another paper chip based on *the recycled paper* instead of the photo paper which was published in our previous report [6]. In this study, we point out the fact that this generalized paper platform could significantly reduce the cost of p-chip further, such that it can provide the affordable technique to yield the benefit especially for people in resource limited regions. Apparently, in fact there is no reason why two papers might be different in the role of a platform as far as the paper is used only as a role of substrate, except only one concerning that a question must be answered what if the recycled paper is enough rigid, no pores and low roughness. The highly electrical insulation for the recycled paper must be verified, especially when there was printed images in the carbon nanotube ink which might cause electrical-short either the electrodes or spoil the uniform electric conductivity. In this reason, we investigated the properties of recycled paper printed with carbon nanotubes (CNTs) ink by using various instruments to verify the quality and capability of recycled paper to be applicable for platform of microfluidic chip.

2 RESULTS AND DISCUSSION

To establish paper as a platform for the active p-chip how to coat a patterned array of electrodes is most important. Printing method with the conductive CNT ink on planar paper should be an easy, quick and inexpensive way as far as the high resolution can be achieved at least less than 500 μm that is one necessary condition for the active microfluidic chip manipulating an about 3 μL drop on it [8]. It can also be the simplest method because designing and printing steps can be incorporated into just one step, being capable replacing the complex, complicated and the multisteps-required conventional lithography method. Here we used a desktop inkjet printer, Epson Stylus T10, with the home-made conductive CNT ink [8]. Employing the desktop inkjet printer may play a critical role for not only simplifying deposition process of patterned array of electrode in sub-micro resolution but also providing an option to choose a low-cost, easy accessible and disposal platform. Previously in order to obtain the best printing quality, we have employed the photo paper since it is properly suitable for inkjet photo printing, due to its strong mechanical strength, high hydrophilic surface and homogenous ink absorption.

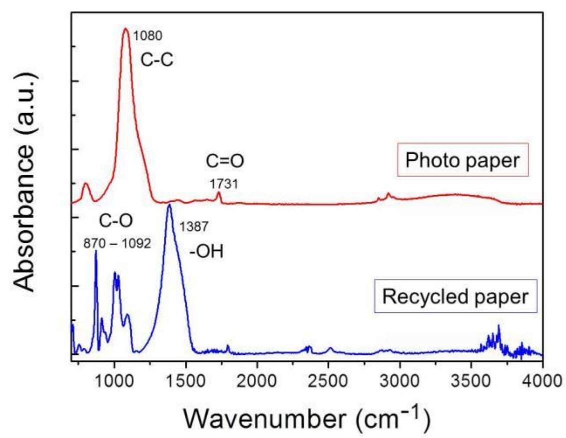

Figure 1: Comparison of two FTIR spectra of the recycled paper and the photo paper. The C-C bond corresponds to the existence of a plastic polymer layer coated on top surface of the photo paper [8], while the cellulose –OH bond indicates no top coating layer on the recycled paper.

Now, we want to investigate the recycled paper which is commonly used as printing material for magazines and newspapers. The most concerning for usage of the recycled paper for the chip platform is any possibility of contamination particularly effected on the electrical insulation. Therefore, to check any chemical composites

NSTI-Nanotech 2014, www.nsti.org, ISBN 978-1-4822-5827-1 Vol. 2, 2014

whatever the conductive binder for producing the recycling paper contains, we compared the Fourier transform infrared spectroscopic (FTIR) spectrum of the recycled paper and that of the normal document paper. As shown in Fig. 1 there is no significant difference explicitly indicating that there is no the chemical composite to effect on the conductivity, unless the paper contains the printed ink that is commonly composited of the conductive carbon black.

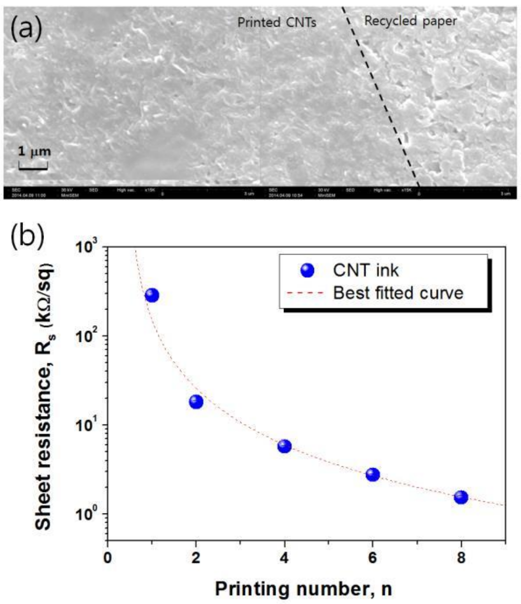

Figure 2: (a) SEM image of the inkjet printed CNTs on recycled paper, (b) the sheet resistance of the CNT electrode printed on the recycled paper

In order to see how well uniformly the CNT ink is printed on the recycled paper that we choose the magazine paper that even contained printed ink images of characters not photos that we expected might influence on the conductivity or even makes electrical-short between electrodes. First, we investigated the morphology of the printed CNT and the pure surface of the recycled paper by the scanning electron microscope (SEM). As shown in Fig. 2a the physical network of CNTs printed on paper can be seen, as observed in the photopaper [6]. The surface resistance as a function of printing times was measured with the four-probe method and is showed in Fig. 2b. It showed that it follows to the percolation theory of the power law (dashed curve). It revealed the critical percolation reached at the first printing time, which is good coincident to the morphological image of well network of CNTs in fig. 2a. One interesting feature is the saturated surface resistance reached at the twelfth printing times with ca. 800 kΩ/sq (for completed graph, see [8]).

The last severe concerning related to the recycled paper substrate should be the roughness that could provoke the punctuation the multilayer films, which are deposited subsequently in submicro thickness, as shown in Fig. 3. For the printed electrodes will be coated with a strong water-resistive and dielectric parylene-C film (2 μm) and then by either hydrophobic Teflon AF-1600 film (ca. 200 nm) or hydrophilic silicone oil film (bottom centre in Fig. 3), resulting that the cellulous fibers in paper were confined only taking a role of a substrate to support these multilayers in current our chip [8]. However exploring the passive property incorporated onto our active chip should be interested as much as it is deserved for our future work because it should be very useful for sensing, detecting and analyzing the drop samples simply by Litmus paper and chromatographic in the wicking way.

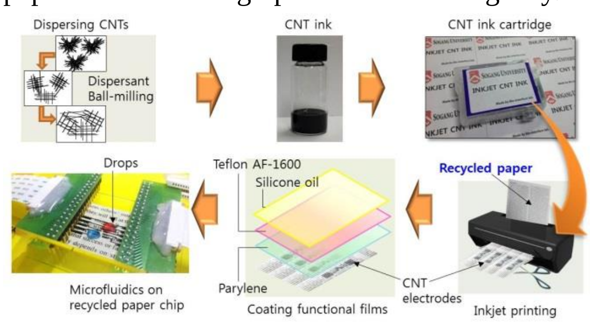

Figure 3: Schematic diagram for active microfluidic p-chip with inkjet printing the CNT ink for the patterned electrodes on recycled paper

To find the proper operating voltage to move the drop by the electrowetting force on the recycled paper, the variation of the contact angle as a function of applied voltage has been measured. Because the voltages of 70 V - 120 V induced the significant reducing contact angle up to corresponding to the saturation contact angle as shown in Fig. 4, we set the driving voltage at minimum 70 V for moving a drop.

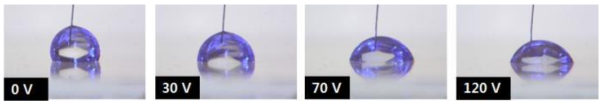

Figure 4: Electrowetting images of a drop on the hydrophilic silicone oil coated on p-chip as a function of applied voltage

Figure 3 shows the schematic views of detailed steps of fabrication of the recycled p-chip and drop actuations on it by using an electric power source and a programmable multiplex switching system. As shown in Fig. 5 we demonstrated the manipulation of drop on the p-chip by supplying the voltage manually: i.e., transporting, merging and mixing operations. To demonstrate the mixing merged drop we indexed two drops in blue and red colors respectively before colliding each other. This simple additive operation suggests that it can be used for analysing certain chemical and biological samples, having reactive each other when are mixed, without any significant modifying the chip structure and design. One interesting feature is the fact that no matter how the conductive carbon black ink is printed on the recycled paper it does not cause any severe problem to short electrically the neighbour electrodes unless they are interconnected nearby the working area where drop motion takes place as marked in yellow in Fig. 5f.

In conclusion, the recycled p-chip showed the good performance for handling the microfluidic drop actuation, which is indeed comparable to that of our previous photo paper chip. It can be used for any potential application to deal with certain biological and chemical aqueous samples, especially when the reacted drop is possible to be detected in colorimetry detection

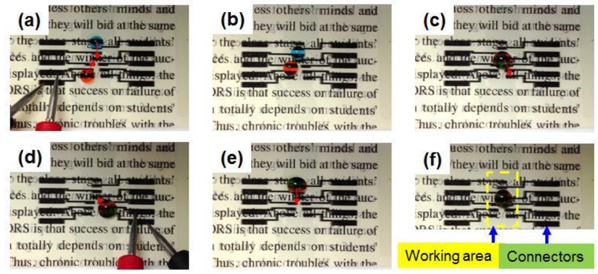

Figure 5: Photo images of successive movement of drops along the patterned rails of CNT electrodes on recycled magazine paper.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Research R&D Program, the Mid-career Researcher Program (2011-0017539), the Advanced Research Center for Nuclear Excellence and Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT & Future Planning, Korea (NRF-2013R1A1A2010265).

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