# Development of "paper transistors" with new structure using carbon-nanotube-composite papers for aiming to construct logic circuits

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## ABSTRACT

We propose new "paper transistors" with unique structure using carbon-nanotube-composite papers (CNTCPs) for aiming to construct "paper logic circuits." One of characteristics of the carbon-nanotube (CNT) we have focused is that it has metallic and semiconducting properties depending on the structure. The CNTCP is a composite material based on the CNTs and the papers (pulps). Therefore, it can show unique properties including a metallic or semiconducting property caused by the CNTs despite of a paper. Previously, we have succeeded in developing "paper transistors." However, the previous paper transistors had some problems including their conductivity. As a solution, we have focused a unique CNT network structure in the composite paper, i.e., a three-dimensional CNT network structure. In concrete, we try to change the shape of the paper transistors and evaluate them. As results of this study, we succeeded in improving the performance of the paper transistors.

***Keywords***: carbon nanotube, paper transistor, paper device, carbon-nanotube-composite paper

## 1 INTRODUCTION

Recently, the carbon-nanotube (CNT) that is one of nano-carbon materials has been receiving increasing attention because it has a lot of excellent characteristics, and is expected to be applied to various objects in wide areas. In concrete, it is known that the CNT has chemical stabilities, high electrical and thermal conductivities. Especially, they show unique electrical properties, i.e., metallic and semiconducting properties that depend on their difference of structure [1]. However, generally, it is hard to handle the CNTs because they exist in the powder state and they are nanoscale materials. As a solution for it, various CNT composites have been proposed. We have also succeeded in developing unique composites by combining ordinary papers, i.e., carbon-nanotube-composite papers (CNTCPs) (Fig. 1) [2]. Our CNTCP shows many properties, e.g., electrical conductivity, resulted from contained CNTs despite a paper. Moreover, it can be metallic-CNTCPs and semiconducting-CNTCPs by choosing and containing the metallic CNTs and the semiconducting CNTs, respectively. Originally, papers are familiar materials in our daily life. Therefore, by using and applying our CNTCPs instead of the ordinary ones, the papers will be able to have electrical and electronical functions in near future. Actually, we have succeeded in developing many "paper devices," for example "thermoelectric power generating papers [3]" and so on.

In this study, we have focused on the electrical characteristics as described above and developed "paper transistors" by combining three types of papers, i.e., metallic-CNTCPs as electrodes, semiconducting-CNTCPs as channels, ordinary papers as insulators. Each paper can be fabricated easily by using a papermaking method based on the Japanese-*washi* papermaking technique. In previous study, we have already succeeded in fabricated a prototype paper transistor [4]. The first one showed a p-type characteristic because CNTs show the p-type semiconductor characteristic in the air [5]. However, it is expected that n-type paper transistors can be fabricated by n-doping CNTs.

The paper logic circuits can be realized by combining p-type paper transistors and n-type paper transistors, but the previous study had problems in the reproducibility of p-type paper transistors. So in this study, to improve reproducibility, the main object is to improve the performance by reconsidering the structure of the conventional type paper transistor and changing some structures.

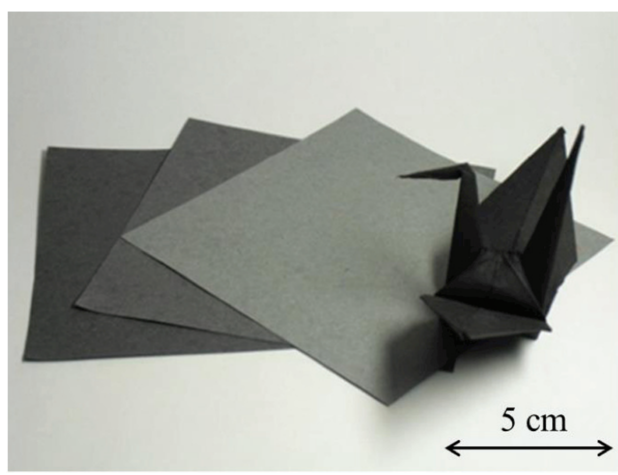


Figure 1: Samples of CNT composite papers. Color Differences depend on contents of CNTs in them.

## 2 EXPERIMENTAL METHOD

In this section, the papermaking method for our metallic- and semiconducting-CNTCPs that are necessary for paper transistor production are described (Sec. 2.1). Then, section 2.2 describes how to fabricate our paper transistor and structural changes from the previous paper transistor to new designed paper transistor.

### 2.1 Papermaking Method for CNT-Composite Paper

Our CNTCPs can be fabricated easily by using a papermaking method based on the Japanese-*washi* papermaking technique. In concrete, firstly CNT aqueous dispersion and pulp (a raw material of the paper) aqueous dispersion are prepared. Then, both dispersion are mixed, contained water is drained, and remained objects are dried and formed to finalize the fabrication (Fig. 2).

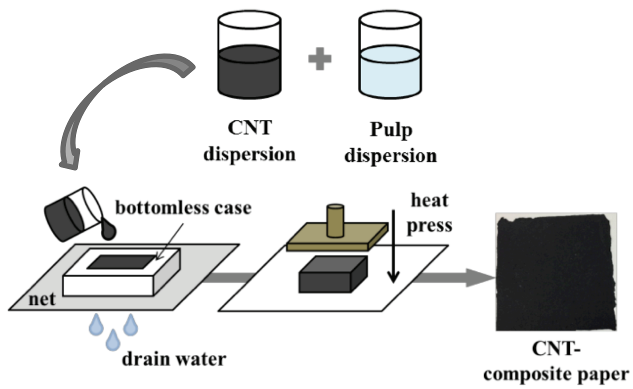


Figure 2: Schematic of papermaking method for CNT-composite paper.

#### 2.1.1 Metallic-CNT-Composite Paper

Here, our papermaking process for the metallic-CNTCP will be described.

I. Preparing 250 mg of the pulp materials, putting them into 25 ml of pure water, and dispersing to prepare the pulp dispersion for the metallic-CNTCP.
II. Preparing 38 mg of single-walled CNTs (HiPco purified SWNTs, provided by NanoIntegris Inc.) and 35 mg of sodium dodecyl sulfate (SDS) as a dispersant for metallic-CNTs.
III. Putting the CNT and SDS into 20 ml of pure water and applying ultrasoication to them for 60 minutes to prepare the metallic-CNT dispersion.
IV. Mixing the pulp dispersion and the metallic-CNT dispersion and applying ultrasonication to them for 30 minutes to prepare the mixed dispersion.
V. Fabricating the metallic-CNTCP by the papermaking method as described above.

The sheet resistance values of metallic-CNTCPs were about 9 Ω/□.

#### 2.1.2 Semiconducting-CNT-Composite Paper

Here, papermaking process for the semiconducting-CNTCP will be descried.

I. Preparing 50 mg of the pulp materials, putting them into 5 ml of pure water, and dispersing to prepare the pulp dispersion for the semiconducting-CNTCP.
II. Preparing 8 ml of semiconducting-CNT dispersion (purity 99%, CNT-concentration 1mg/100ml, IsoNanotubes-S, provided by NanoIntegris Inc.).
III. Mixing the pulp dispersion and the semiconducting-CNT dispersion and adding 0.5 ml of polyethylene oxide solution (PEO, 1 wt. %) as a flocculant.
IV. Putting the mixture in oven (80℃) and evaporating some moisture to make CNT entangle with pulp by function of flocculant.
V. Fabricating the semiconducting-CNTCP by the papermaking method as described above.

### 2.2 Method of Fabricating "Paper transistor"

The basic "paper transistor" is fabricated by combining two types of the CNTCPs and ordinary papers as insulators (Fig. 3). In previous study, we have already succeeded in fabricated a prototype paper transistor [4]. In this study, we modified the structure to improve the performance of our paper transistor. In this section, we describe how to fabricate "previous paper transistors" and "new designed paper transistors."

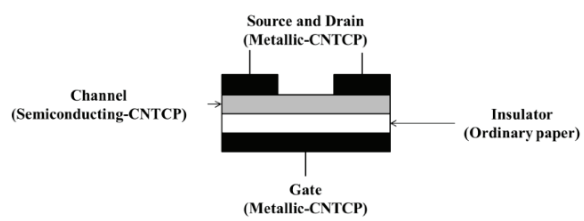


Figure 3: Basic structure of "paper transistor"

#### 2.2.1 Previous Paper Transistor

The structure of the previous paper transistor is shown in Fig. 4. From the previous study, the aspect ratio of the source and drain electrodes is decided as approximately 3 mm : 4 mm, and the channel has 1 mm of a channel width and 2 mm of a channel length. Also, the thickness of the ordinary paper as the insulator is 0.04 mm.

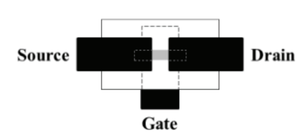


Figure 4: Previous paper transistor

### 2.2.2 New Designed Paper Transistor

In this study, we change some structure of the previous paper transistor, and measure the characteristics of new one.

#### (a) Change of Electrodes Structure

We consider that CNTCPs have structural influences compared with a conventional metal plate, because CNTs have three-dimensional network structures in the CNTCP. And we consider that its network structure causes a unique property for the current flow. Further, the current value decreases due to the resistance of the CNTCP itself. Therefore, to flow current to the channel by fewer CNTs efficiently, we change the structure of source and drain electrodes (Fig. 5).

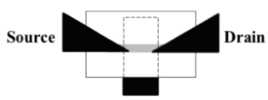


Figure 5: New designed paper transistor

#### (b) Change of Insulator

In addition to changing the electrode structure, we change the insulator for the purpose of improving gate controllability. Previously, the paper with 0.04 mm thickness was used as the insulator. We here prepare the paper of 0.032 mm in this time, so we use that paper as the insulator. Reducing the thickness of the insulator, it is expected that the influence of the gate voltage the semiconducting-CNTCP become larger for the channel, and the on/off ratio can be improved by suppressing the off current.

#### (c) Lengthening Channel Length

Generally, enhancement type transistors are often used for logic circuits. However, from previous study, our paper transistors have been confirmed to have depletion type characteristics. It is thought that this is caused by some paths due to metallic impurities in the channel. Therefore, in order to reduce such paths and bring it closer to the enhancement type, we lengthen the channel length from 2 mm to 4 mm and measure its characteristics.

## 3 EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results of our paper transistors by the structural changes are shown below. In the following subsections, the evaluation of the change of electrodes structure is described (Sec. 3.1), the evaluation of the change of the insulator are described (Sec. 3.2), and the evaluation of lengthening the channel length are described (Sec. 3.3).

### 3.1 Change of Electrodes Structure

Figures 6 and 7 show the measurement results of the previous electrodes structure and the new designed ones. As a result, we succeeded in increasing the drain current value and obtaining more stable gate controllability with the new structure. From these results, we consider that controlling or forming the network of CNTs in the CNTCP will be very effective to improve its performance.

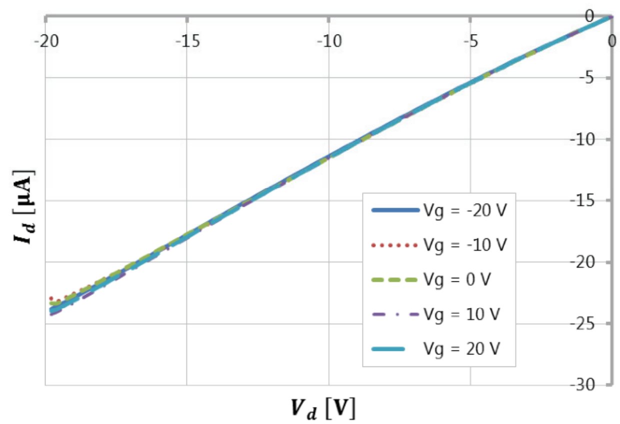


Figure 6: $V_d$ - $I_d$ characteristics of sample with previous electrodes structure.

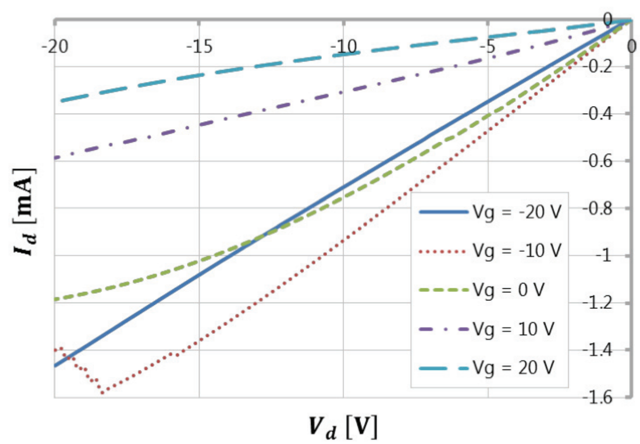


Figure7: $V_d$ - $I_d$ characteristics of sample with new electrodes structure.

### 3.2 Change of Insulator

The measurement result when the thickness of the insulator changed to 0.032 mm is shown in Fig. 8. By using the thinner paper for the insulator, the gate controllability was improved. It is considered that the influence of gate voltage effectively reached the channel due to thinner insulator. Also, the on/off ratio was improved and succeeded in realizing on/off ratio more than 10 times as compared with using 0.04

mm paper. From these results, when thinner paper than the one used in this study is used as the insulator, it is expected that further improvement of the on/off ratio.

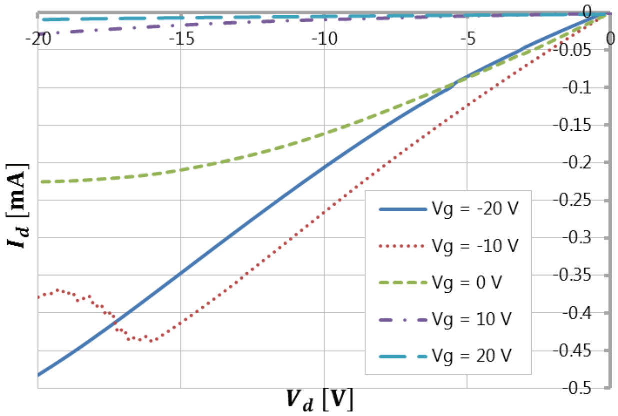


Figure 8: $V_d$ - $I_d$ characteristics of sample with using 0.032 mm paper as insulator.

## 3.3 Lengthening Channel Length

Figures 9 and 10 show $V_d$ - $I_d$ characteristics of the new paper transistors with 2 mm and 4 mm of the channel length, respectively. When the channel length was extended to 4 mm, the leakage current ratio decreased entirely. In other words, we succeeded in that the paper transistor which showed depletion type characteristics was brought close to enhancement type, although the drain current value also decreased. This is because the path due to metal impurities between the source and the drain is reduced asdesired.

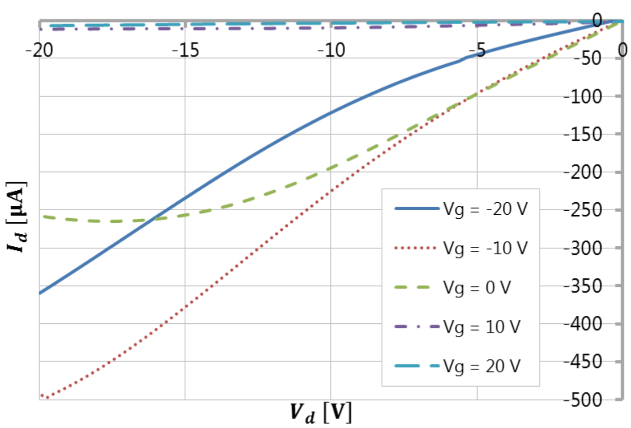


Figure 9: $V_d$ - $I_d$ characteristics of sample with 2 mm of channel length.

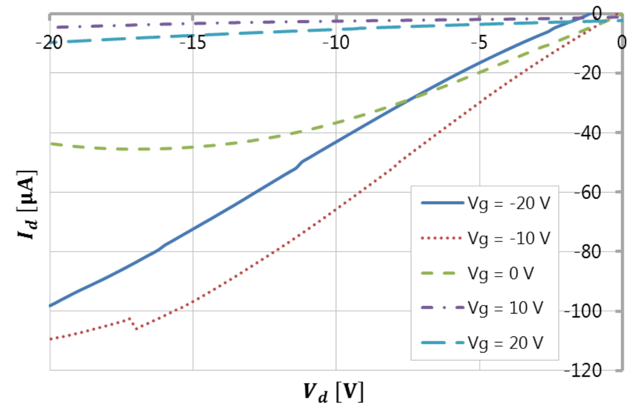


Figure 10: $V_d$ - $I_d$ characteristics of sample with 4mm of channel length.

## 4 CONCLUSION

In this study, we succeeded in improving the performance of our paper transistor by changing the structure from the previous paper transistor. As previously mentioned, the CNTs have three-dimensional network structures in the CNTCP. Therefore, to improve the performance of our paper transistor, we considered that it was necessary to design the effective structure of the CNTCP. From results of this study, we were able to find the performance improvement of our paper transistors.


## ACKNOWLEDGEMENT

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## REFERENCE


[1] V. N. Popov, "Carbon nanotubes: properties and application," Materials Science and Engineering: R: Reports, 43 (3), pp. 61-102, 2004.

[2] T. Oya and T. Ogino, "Production of electrically conductive paper by adding carbon nanotubes," Carbon 46, pp. 169-171, 2008.

[3] K. Kawata and T. Oya, "Development and evaluation of 'thermoelectric power generating paper' using carbon-nanotube-composite paper," Japanese Journal of Applied Physics, 56, 06GE10(5 pages), 2017.

[4] K. Matsui and T. Oya, "Construction of unique logic circuits using carbon-nanotube-composite paper," The 2015 International Chemical Congress of Pacific Basin Societies, MTLS 1407, 2015.

[5] V. Derycke, R. Martel, J. Appenzeller, and Ph. Avouris, "Carbon nanotube inter- and intramolecular logic gates," Nano Lett., 1 (9), pp. 453-456, 2001.