Planar Fashionable Circuit Board Technology and Its Applications

Seulki Lee, Binhee Kim, and Hoi-Jun Yoo

***Abstract*—A new flexible electronics technology, named P-FCB (Planar Fashionable Circuit Board), is introduced. P-FCB is a circuit board technology implemented on the plain fabric patch for wearable electronics applications. In this paper, the manufacturing of P-FCB, and its electrical characteristics such as sheet resistance, maximum current density, and frequency characteristics are reported. The fabrication methods and their electrical characteristics of passive devices such as resistor, capacitor, and inductor in P-FCB are discussed. In addition, how to integrate silicon chip directly to the fabric for the flexible electronics system are described. Finally, examples of P-FCB applications will be presented.**

***Index Terms*—Flexible circuit board, fabric, wearable computer, planar fashionable circuit board, P-FCB**

I. INTRODUCTION

In these days, people pay attention to the wearable computer for daily applications of healthcare or entertainment. Until now, these wearable computers were implemented on the traditional PCBs or flexible circuit boards (FCBs). The PCB substrate has hardness of feeling so that it is not suitable for wearable applications, and although the FCB substrate has better flexibility than PCB, it still cannot support the fully comfortable feelings for users. To overcome this limitation, H. Kim proposed a new flexible electronics technology named P-FCB (Planar Fashionable Circuit Boards) in 2008 [1]. It is a circuit board technology implemented on the plain fabric patch for wearable electronics applications. It can support very soft and flexible feelings just same as clothes. Some characteristics of P-FCB were introduced in [1, 2], and this paper will provide more systematic and profound measurements on P-FCB characteristics.

The rest of the paper is organized as follows. In Section II, P-FCB will be introduced as the proposed wearable technology. The manufacturing process and parameters of P-FCB will be compared to those of the PCB. Also the electrical characteristics and mechanical characteristics of P-FCB will be explained. And the passive devices using P-FCB are shown. Section III describes the applications of P-FCB, especially focused on the daily healthcare applications. Finally, conclusions will be made in Section IV.

II. PROPOSED WEARABLE TECHNOLOGY: P-FCB

1. Manufacturing process of P-FCB

There are two kinds of printing circuit technology including thick and thin film technology [2]. In this paper, only thick film technology of screen printing process is introduced since it is more widely used due to its lower cost. The standard thick film process is comprised of printing and annealing. Some processes are correspondent with those of PCB manufacturing process. The comparison between PCB and P-FCB manufacturing process is summarized in Table 1. And the parameter comparison between PCB and P-FCB is shown in Table

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2. The all PCB parameters are based on [3], and P-FCB parameters are measured with the screen printing environment of [2]. In Table 2, it is shown that P-FCB parameters are comparable to the PCB parameters so that P-FCB system can replace the PCB applications.

Fig. 1 shows the DC resistance characteristics according to the various annealing temperature and time. The DC resistance is decreased when the annealing temperature is higher or the annealing time becomes longer. But higher annealing temperature or longer annealing time can makes the fabric deformed. Therefore, proper temperature and time should be determined. Fig. 1 shows the DC resistance of the silkscreen printed line with 10 cm length and 1mm width. The conductive ink named CSP-3163 is used to print the line on the fabric [2]. Annealing time is fixed as 20 minutes in Fig. 1 (a), and the annealing temperature is fixed as 200°C in Fig. 1 (b). According to the measurement results in Fig. 1 (a) and (b), respectively, 300°C of annealing temperature and 2 hour of annealing time is shown to be most suitable since the DC resistance goes into the steady-state after that temperature and time.

After manufacturing a circuit board on fabric, several ICs should be attached to it to complete the system. The remaining process for manufacturing P-FCB system is shown in Fig. 2. First, the target IC and small metal beads are physically attached to the fabric. And thin gold wires are used to connect the pads of the IC and the circuit board. Finally, the IC and beads are molded into a package with liquid molding epoxy. It can provide highly robust protection against potential pressure on the packaged chip.

Table 1. Manufacturing Process Comparison.

	PCB	P-FCB
Step 1	Artwork	Mask production
Step 2	Exposing	Screen printing
Step 3	Etching	Annealing
Step 4	Tin-Plating	Covering
Step 5	Drilling	-
Step 6	Shaping	-

Table 2. Manufacturing Parameter Comparison.

	PCB	P-FCB
Min. trace width	0.1mm	0.1mm
Min. via size	0.75mm (via)	2mm
	1.5mm (barrel)	
Min. trace spacing	0.1mm	0.2mm
Other min. spacing	0.1mm	0.2mm

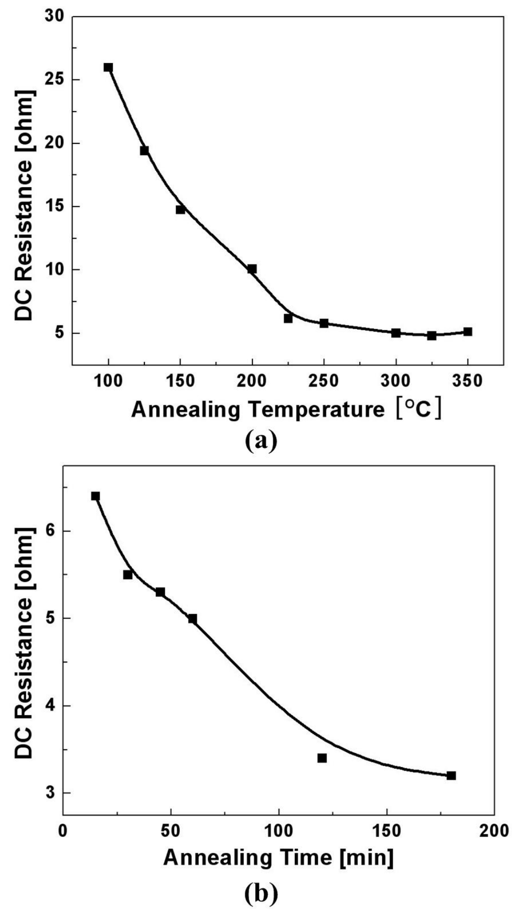

Fig. 1. Relationship between dc resistance and annealing parameters.

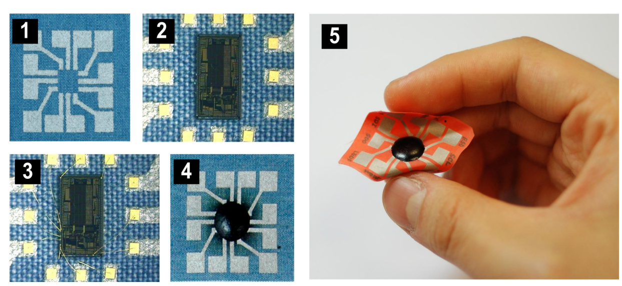

Fig. 2. P-FCB system manufacturing process.

2. Electrical characteristics of P-FCB

To check the frequency characteristics of P-FCB, 10 cm long and 0.5 mm width wires are manufactured and tested. With Vector Network Analyzer (VNA), S21 parameters are measured so that the transmission efficiency is calculated. The measurement results are shown in Fig. 3. The bandwidth, which is defined as the frequency range from 0 Hz to below -3 dB in the frequency response, is about 20 MHz. The transmission efficiency at low frequency and the 3 dB bandwidth is changed according to the annealing time and temperature. However, the frequency characteristics at high frequency over 3 dB bandwidth are similar to each other. Since lower resistance makes the transmission more efficiency, higher annealing temperature and longer annealing time is desired. And considering the deformation of fabric substrate during annealing process, it is shown that 300°C of annealing temperature and 2 hour of annealing time is most suitable as described in section II-A.

Fig. 4 shows the crosstalk measurement between a signal line and a neighboring line of 15 cm length. The signal amplitude of the aggressor is 2.5 V with a 6 ns of rising time. The space between two lines is 6 mm. As shown in Fig. 4, the noise signal on the victim wire is 0.14 V, which is under 5.6% of the aggression signal.

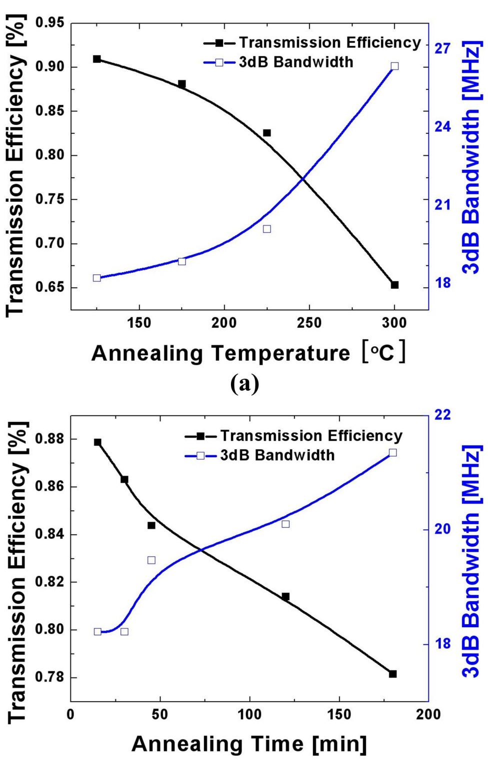

Fig. 3. Frequency characteristics of P-FCB according to (a) Annealing temperature with 20 minutes annealing time (b) Annealing time with 200°C annealing temperature.

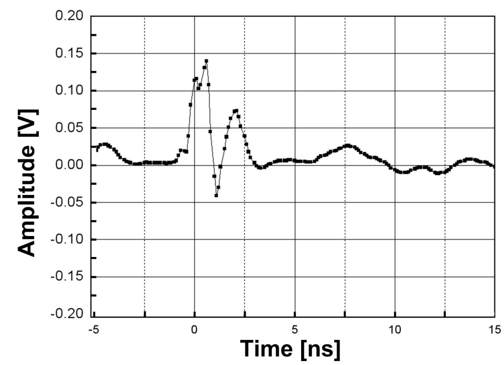

Fig. 4. Crosstalk measurement of P-FCB wires.

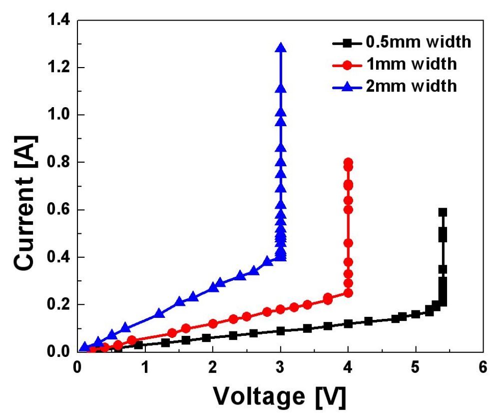

Fig. 5. Maximum current density measurement of P-FCB.

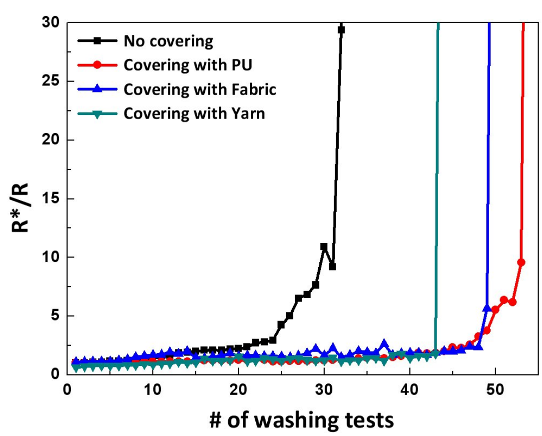

Fig. 6. Washing test results of P-FCB.

The final measurement for electrical characteristics of P-FCB is about the maximum current density. The maximum current density is an important electrical characteristic since it determines the stability of the system against power consumption. Fig. 5 represents the measurement results on the maximum current density of P-FCB wires. It differs from the wire length and width because a wire resistance is changed according to them.

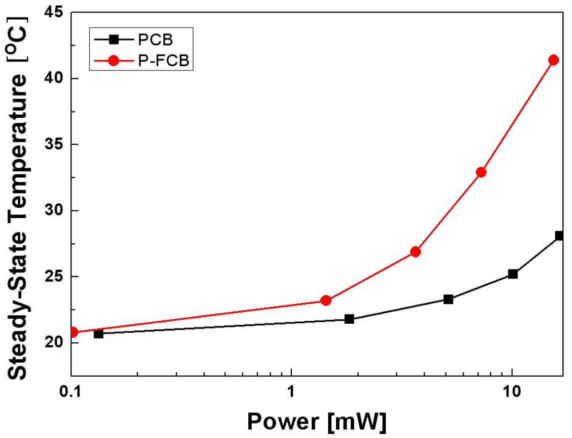

Fig. 7. Comparison of heat dissipation between P-FCB and PCB.

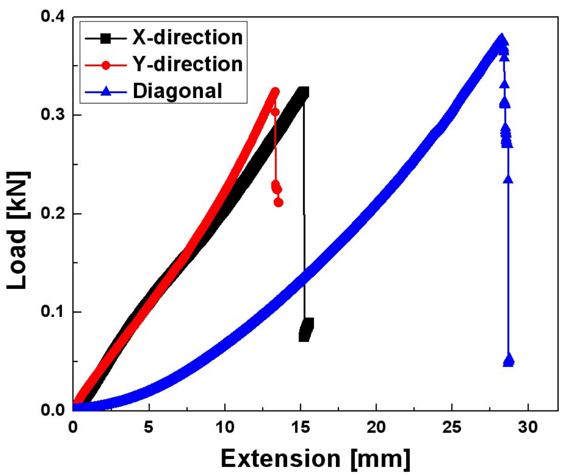

Fig. 8. Durability to tear of P-FCB system.

Table 3. Fabric Characteristics.

Characteristics	Value
Yarn fineness (tex)	4.4
Fabric density (dm^{-1})	500
Volume resistivity	-
Dielectric permittivity (ε_r)	4.0
Dielectric strength (kV/m)	-

As described before, annealing temperature and annealing time affect the wire resistance so that it also affects the maximum current density. In this measurement, 300°C and 2hour annealing environment is used. As shown in Fig. 5, 0.17 A, 0.2 A, and 0.4 A of current will be stood for 0.5 mm, 1 mm, and 2 mm of the wire width, respectively. The linear region at low voltage of the graph is caused by wire resistance.

3. Mechanical characteristics of P-FCB

The durability to washing of P-FCB system is shown in Fig. 6. Three covering methods are introduced, and non-covered P-FCB is also measured as a reference. As shown in Fig. 6, all of covering methods show better durability to washing than P-FCB itself without covering. However, even for non-covered P-FCB, it passes over 30 times of washing tests. This mechanical durability to washing is enough for wearable system embedded in our everyday dress. So we can add the covering process only when the specially enhanced durability is required.

Fig.7 shows the comparison of heat dissipation between P-FCB and PCB. The measurement result represents that P-FCB has worse characteristics for heat dissipation than PCB above 1 mW of power. This result becomes the important indicator of P-FCB system design. To make P-FCB system operate safely, it should consume power less than 1 mW. Within this power range, the operating

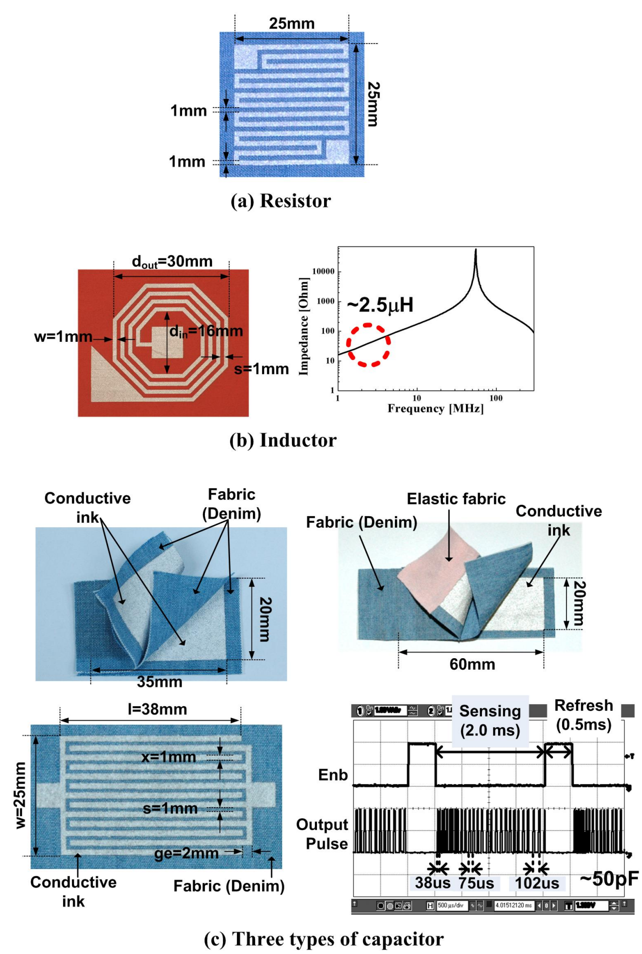

Fig. 9. Passive devices using P-FCB.

Table 4. CSP-3225 Characteristics.

Characteristics	Value
Solid Content	41.79
Viscosity	190
Fineness of Grind (FoG)	5
Specific Gravity	1.27
Adhesive Strength	100/100
Resistivity	3.28
Crease Test	4.80
Pencil Hardness	3

temperature of P-FCB system does not increase over 5% of PCB system. Otherwise, P-FCB system may suffer from excessive heat dissipation which induces high operating temperature and fault operation.

The durability to tear of P-FCB system is measured as shown in Fig. 8. The measurement in this study is performed by using the fabric made with polyester (PES). And it is revealed that the durability of fabric is weaker than that of conductive ink on it so the durability to tear of P-FCB system mainly depends on the type of fabric. In our system, almost 300N of x- or y-directional force can be withstood without any defect. And it can endure 380N of force with 28 mm extension in diagonal direction. Note that it is the result of a specific fabric made with PES whose characteristics are represented in Table 3, so it can be changed according to the fabric substrate in P-FCB system. And by considering our everyday dress, the durability to tear is strong enough.

4. Passive devices using P-FCB

In the conventional PCB system, surface-mounted type of passive devices such as resistor, capacitor, and inductor are used. However, in the proposed P-FCB system, these passive devices can be implemented using same fabrication process as a circuit board. Fig. 9 shows the examples of passive devices using P-FCB. The sheet resistance of the resistor is 45.8 Ω/□ when 3 times of printing with 300°C and 2 hour annealing is performed. To make the resistor, new conductive ink named CSP-3225 is employed which has larger resistance and equal flexibility compared with CSP-3163. The characteristics of CSP-3225 are summarized in Table 4.

Three types of capacitor and one type of inductor is also proposed in Fig. 9. The capacitance range is between 1 pF and 100 pF [2], and the inductance range is between 100nH and few μH [2], [5]. Using a capacitor sensing system on P-FCB, the capacitance can be calculated [1]. As shown in Fig. 9 (c), the number of output pulses from the IC is increased by larger capacitance. So we can count the number of output pulses to see the target capacitance. Also we can estimate the inductance by using LC tank and phase difference [6]. To make the product of inductance and known capacitance constant, we can see the inductance variation. If the carrier frequency of the clock signal is also known, then we can calculate the inductance exactly. By using these passive devices, P-FCB system can increase the wearability compared to PCB system.

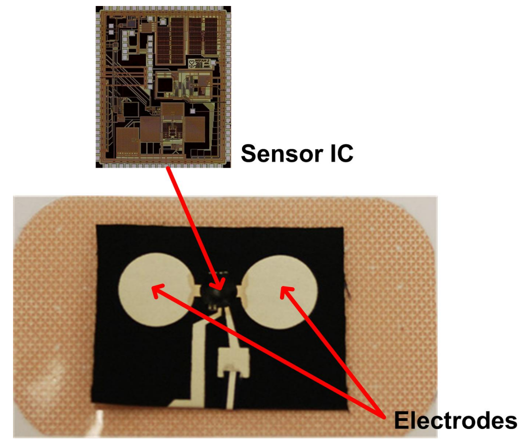

Fig. 10. ECG sensor node using P-FCB [4].

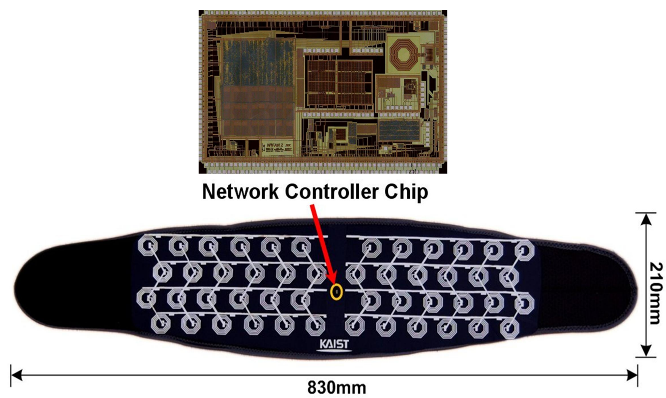

Fig. 11. Inductor channel array implemented on the chest band [4].

III. Application of P-FCB

Basically, all systems which can be implemented with PCB are potential applications of P-FCB. Among them, the most appropriate application is healthcare system if we pay attention to the wearable characteristics of P-FCB. Several healthcare systems using P-FCB were introduced [1], [2], and [4], and all of them are more suitable compared with previous PCB systems. In this section, some examples of P-FCB applications are presented.

Fig. 10 shows the ECG sensor node which is implemented with P-FCB. It is already shown that these sensor nodes can be implemented as a band-aid type [4]. The electrodes are placed on the fabric, and sensor AFE and transceiver circuits are integrated into the SoC of P-FCB. So the fabric patch is in charge of both sensing and data transmission. To reduce the thermal and 1/f noise from the P-FCB electrode, sensor AFE circuits adopts the chopping techniques as in [7]. The data transmission in [4] is performed by inductive coupling. The communication channel is a pair of inductor which is described in section II-D. And the inductor channel array used in [4] is shown in Fig. 11. It is a kind of chest band what people sometimes use in daily life. As shown in Fig.11, P-FCB also has high potential in the channel of near-field communication for wearable computer. Since near-field communication is suitable for communication in the wearable computer field due to its low power consumption characteristic [5, 6, 8], P-FCB system can be widely used in that area. Although the flexibility of P-FCB becomes a problem in this application since the inductance can be changed during communication, the compensation technique is proposed so that it makes the communication more reliable [6].

VI. CONCLUSIONS

A new flexible electronics technology named P-FCB is introduced. Fabrication process and comparison with PCB are represented. And some electrical and mechanical characteristics are measured to see the suitability of P-FCB to wearable computer applications. The measurement results reveal that P-FCB can be a good circuit board as previous PCB with improved flexibility. Finally, the applications of P-FCB are shown that P-FCB has a great potential to the healthcare system and wearable system.

V. ACKNOWLEDGMENT

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