Electrical Characterization of Screen-Printed Circuits on the Fabric

Yongsang Kim, *Student Member, IEEE*, Hyejung Kim, *Student Member, IEEE*, and Hoi-Jun Yoo, *Fellow, IEEE*

***Abstract*—Fabrication methods of planar printed circuits on fabrics are introduced and their electrical characteristics are measured and analyzed. Wet patterning method like screen printing as well as dry process of sputtering are used to fabricate the patterned film electrodes on various types of fabrics. The minimum width of the patterns is 0.2 mm for screen printing and 0.1 mm for gold sputtering, and the typical sheet resistance is 134 m $\Omega/\Box$. Fabrication methods of capacitors of 1 pF–1 nF and inductors of 500 nH–1 μH at 10 MHz on the fabrics are also introduced. Bonding and packaging of silicon chip directly on the fabric circuit board are proposed and their mechanical properties are investigated. The ac impedance of the transmission line is measured as 201–215 Ω with $<7.4\%$ variation, and the time-domain reflectometry profile shows that the -3 dB frequency of the printed transmission line of 15 cm on the fabric is 80 MHz. A complete system composed of a fabric capacitor sensor input, a controller system-on-a-chip, and an LED array display is implemented on the fabric and its operation is demonstrated successfully.**

***Index Terms*—E-textile, fabric, electrical characterization of fabric, packaging, planar-fashionable circuit board (P-FCB), silk-screen printing, sputtering, transmission lines, wearable computing.**

I. Introduction

IT is widely expected that many portable electronic devices such as cell-phones and MP3 players, now carried in the pockets or arm bands, will be integrated in the clothes itself for the convenience and mobility. Consequently, on the clothes more functions than just climatic protection and a good look are expected to be integrated in the near future. Although such wearable computer concepts have been actively studied by many research groups over the decades, still they are not fashionable and comfortable to wear in daily life because of their bulky sizes and bad human–computer interactions [1]. The e-textiles which mean that the computing and communication functions are integrated into the textile itself, will be more flexible, unobtrusive, robust, small, inexpensive, washable, biocompatible with human skin, and aesthetically acceptable [2].

There have been a number of e-textile researches focused on conductive threads or yarns to integrate electronics into fabrics [3]–[7]. Georgia Tech Wearable Motherboard (GTWM) used optical fibers to interconnect sensing, monitoring and information processing devices together [3]. Massachusetts Institute of Technology (MIT) and Virginia Tech studied woven metallic organza or piezoelectric materials for the fabric keyboard and music jackets [4], [5]. Cottet has studied electrical characteristics of polyester yarns that are twisted with a copper (Cu) filament [6]. Jung and Locher proposed a conducting band interconnection technology between textiles and electronics [7], [8]. However, all of these approaches used just the conducting threads or yarns for interconnection of electronic devices with fabrics, and only perpendicular wiring structure is possible due to the intrinsic characteristics of fabric weaving. In addition, the insulating materials coating the conductive yarns in e-textiles should be removed by the laser blowing process or by a mechanical stripper to make the electrical junctions for the formation of the circuit path [7]. These interconnection processes have to be performed one by one resulting in low productivity and connection errors or electrical discontinuity are not negligible. In addition, for the integration of integrated circuit (IC) with fabric, they placed the packaged chip on the interposer which felt stiff and obtrusive because of its different hardness and temperature expansion coefficients [7], [8]. Moreover, their limited fabric selection restricts freedom in the aesthetic issues which are very important in fashion industry.

Recently, Kim, *et al.* proposed a new paradigm of electronic textile, planar-fashionable circuit board (P-FCB) [9]. They apply thin and thick film processes on the fabric directly to form the patterned electrodes for the integration of the electronics with fabric. In analogy, its direct circuit printing on a fabric can be compared with the planar semiconductor process which has replaced the bulk process. In addition, it is a new type of package technology to integrate system-on-a-chip (SoC) on the fabric very close to the human body. Once its reliability is confirmed, the P-FCB may bring about thin, light, low cost, and human compatible package containing electronics inside. Since the thickness of the common fabric is 100 μm and the patterned films on P-FCB are 10 μm thick, the packages can be folded or wrapped freely like the plain clothes enabling P-FCB technology to be the genuine e-textiles.

In this paper, the thick and thin film processes on fabric will be proposed and their electrical characteristics will be evaluated to investigate the performance and limits of the printing circuit technology. In Section II, the test of the various types of fabrics will be reported for the selection of the optimal fabric substrate of the printed circuits. The dc and ac electrical parameters of P-FCB transmission lines will be analyzed in Section III. The passive circuit elements such as R, L, and C formed on the textile will be explained, and the bonding and packaging of the silicon chip on P-FCB directly will be introduced in Section IV.

Manuscript received March 10, 2008; revised June 26, 2009. First published December 04, 2009; current version published February 26, 2010. This work was recommended for publication by Associate Editor B. Kim upon evaluation of the reviewers comments.

The authors are with the Division of Electrical Engineering, Department of Electrical Engineering and Computer Science, KAIST, Daejeon 305-701, Korea (e-mail: seeseah@gmail.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TADVP.2009.2034536

TABLE I
VARIOUS TYPES OF FABRIC [11], [13]

Type	Yarn Fineness (tex)	Fabric density (thread/10^{-1}m)	Resistivity (Ω·m)	Dielectric permittivity ε_r	Dielectric strength (kV/m)	Thermal Conductivity (W·m^{-1}·K^{-1})
Cotton	20	211	1.76×10^{12}	1.3	45.0	0.03
Viscose	21	479	3.62×10^{11}	5.4	6.8	-
Silk	8	493	2.40×10^{13}	3.0	-	0.12
Wool	43	312	2.30×10^{13}	3.5	-	0.07
PES #1	5.5	210	4.35×10^{13}	2.8	-	0.16
PES #2	5.5	300	-	4.1	-	-
PES #3	4.4	500	-	4.0	-	-

In Section V, a system integration example integrating a SoC, a fabric capacitor sensor, and LED arrays on a single cloth will be introduced. Finally the conclusion will be made in Section VI.

II. PRINTING PLANAR CIRCUITS ON FABRIC

In this paper, the printing circuit technology including thick and thin film technology is proposed for the integration of electronic devices on the fabrics. The thick film process is screen printing, and the thin film process is sputtering deposition. The proposed planar circuit printing approaches can make entire electronic circuits on a planar fabric board at once and also reproduce the identical circuit boards repeatedly, resulting in low cost, high productivity, and high quality circuit board, just as the electronic printed circuit board (PCB) technology does, which makes the current electronic industry possible.

A. Fabric Substrate

Fabrics, woven with synthetic fiber, such as polyester (PES), as well as natural fiber, such as cotton and wool, are tested for the possible substrates of the planar-fashionable circuit board (P-FCB), instead of polyimide or Flame Retardant 4 (FR4) which are mainly used in electronic PCB [10]. However, the detail electrical characteristics of the fabrics are not reported in the recent literatures except only limited information related with electromagnetic interference (EMI) shielding, static dissipation, and resistive heater applications [11]–[14]. In this study the fabrics made with cotton, wool, viscose, polyester (PES), and polyacrylonitrile (PAN) are tested. Viscose is made with fibers of regenerated cellulose obtained by the viscose process, and PAN is fabricated with fibers composed of synthetic linear macromolecules [13].

The electrical and geometrical parameters of the investigated materials are summarized in Table I. Three types of polyester fabrics with different yarn fineness and fabric density are used in this experiment. The fineness of yarn is expressed with the unit of "tex" which is defined as the mass in grams per 1000 m (g/km), and the texes of the investigated materials are 4.4–43. The electrical resistance of textile materials is strongly dependent on the humidity of the environment. Table I shows the measured resistance values of the fabric samples at a relative humidity of 35%. Practical dielectric permittivity of the fabric can be extracted by measuring the capacitance values of the parallel plate capacitors using the fabric as its dielectric material. Even though it was known that the measured permittivity strongly depends on the ratio of fiber and air, they are given from 1.3 to 5.4 at a relative humidity of 35% [11], [13].

The electrical resistance of film wire and the electrical stability of the electrical junction on the P-FCB are mainly dependent on the roughness of surface of the fabric substrate. To reduce the resistance and to maintain the stability of connection, the dense fabric with thin yarn is better. In addition, since conductive ink consists of metal, e.g., silver, which dries rigid after drying and firing, the elasticity of the substrate fabric may destroy the integrity of the metal wire films on it. Therefore, PES of type #3 in Table I with the densest fabric and the finest fiber is chosen as the fabric substrate for P-FCB owing to its small elasticity.

B. Thick Film Process: Screen Printing

Thick film process is a simple and low-cost process which is well established in electronics industry to make complicated electronic circuitry on the plastic boards [15]. In this paper, we propose that the silk-screen process can be also applied to form the circuit patterns onto fabrics. The standard thick film process is comprised of printing, drying, and firing. These processes have been widely used in textile industry to form embroider patterns on the fabrics even before it was adopted to fabricate electronic PCB. The proposed technology, however, uses a conductive ink to form the electronic circuits rather than to use simple colored ink to paint figures on the clothes. The conductive ink is painted through the open areas of a mesh-reinforced stencil onto the substrate fabric like the common silk screening process, and alignment for geometric accuracy can be achieved with common screen printing equipments. The conductive paste consisting of silver, polymer, solvent, polyester, and cyclohexanone is used as the silk screen ink due to its high conductivity and adhesivity to the fabrics. Of course, its adhesivity can be varied with the amount of adhesives in the ink. Table II shows the screen printing parameters and Table III summarizes the characteristics of the conductive ink. The firing process is performed below 150 °C for 20–30 min to avoid the deformation of the fabric substrate.

Fig. 1 shows the film wires of 0.2–1 mm width and 2 cm length formed on the fabric. The minimum line resolution of 200 μm can be achieved. The SEM image of the cross section of the film wire on the fabric and its surface microphotograph are shown in Fig. 2(a) and (b), respectively. In this experiment,

TABLE II
SCREEN PRINITNG PARAMETERS

Mesh	ST250
Mesh Angle	22.5°
Mesh Tension	X:0.75mm Y:0.75mm
Mesh Thickness	66µm
Squeegee Durometer	70
Print Pressure	275.8kPa (40PSI)
Print/Flood Speed	3.5cm/s

TABLE III
CHARACTERISTICS OF CONDUCTIVE INK (CHANGSUNG CORP. CSP-3163)

Solid Content	59.61%
Viscosity	252 Poise
Fineness of Grind	3µm
Specific Gravity	1.86g/cc
Resistivity	5.34×10^{-7}
Crease Test	5 Times
Penscil Hardness	3H

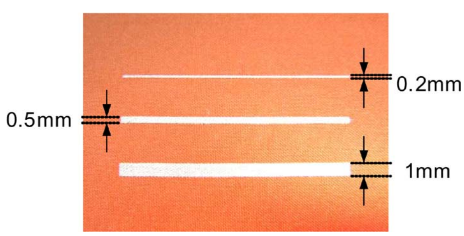
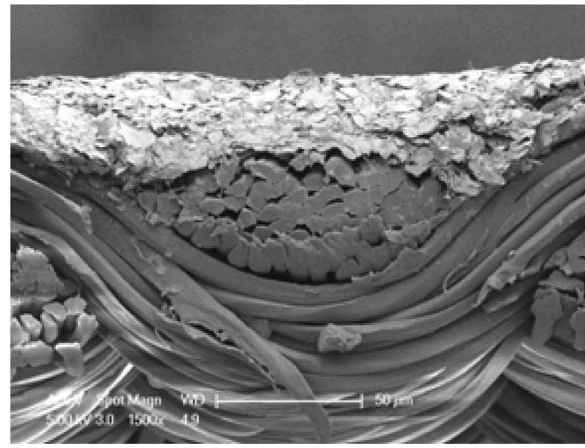


Fig. 1. Screen printed wires on fabrics.

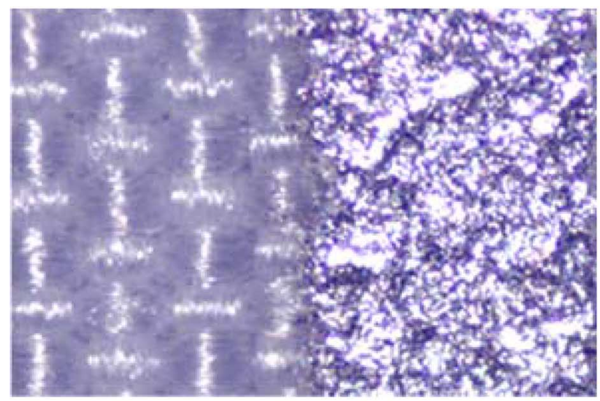
the 100-μm-thick polyester fabric is used as the fabric substrate and the thickness of the film wire is 10 μm.

C. Thin Film Process: Sputtering

Sputtering process can be used to form the high resolution circuits on the fabric. The gold (Au) target is used for the sputtering with Ar inert gas plasma, and the fabric is rolled up on the roller in the vacuum chamber. A shadow mask with the circuit patterns formed in it is placed on the fabric, and Au atoms are sputtered on the fabric passing through the mask to form the electrical circuits. The vacuum level is 10^{-3} torr and the substrate temperature is 150 °C. The minimum line width of the sputtered patterns is 100 μm and the thickness is 1 μm. Fig. 3(a) shows an example of 12 pin pads for IC packaging by sputtering process and its surface microphotograph is shown in Fig. 3(b). Sputtering process provides electrically rigid connection and good washing endurance, but when compared with screen printing, its process is relatively expensive and time consuming. Since the thickness of thin film wire is thin, the roughness of the fabric surface is critical for the fine resolution of the patterns.



(a)



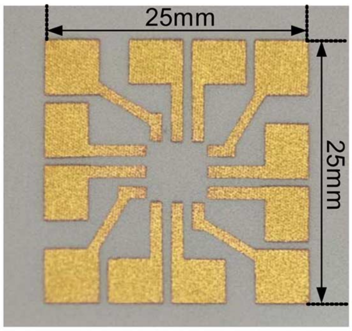
(b)

Fig. 2. Ag screen printed P-FCB. (a) SEM image of the cross section 1500 × magnified). (b) Microphotograph of the surface 100 × magnified.

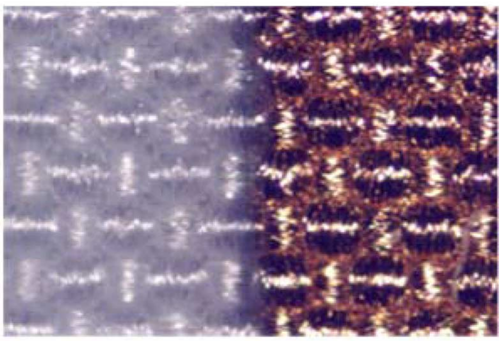
III. ELECTRICAL CHARACTERISTICS OF THE PATTERNED CIRCUITS

Even though EMI shielding, static dissipation, and resistive heater have used the conductor printing process on the fabric, they are printed onto overall fabric surface without any specific patterns [14]. The P-FCB is the first of the patterned conductor printing on fabric for direct chip integration with fabric. In general, it is difficult to use fabrics as the substrates of the circuit boards because they are not as dense as the plastic boards and not so rigid that they can be easily wrinkled. In addition, only limited electrical properties about them are available so that it is impossible to predict accurately their electrical properties as the signal transmission medium.

In this paper, their electrical characteristics are investigated in detail. In order to evaluate the performance and limits of the signal transmission lines on the fabric, we fabricate parallel film wires of the various widths, thickness, and the space between them. Their dc resistance, ac impedance, and maximal signal frequency are investigated by time-domain reflectometry (TDR) profile and frequency characterization. The dc resistance of the line will give an idea of the overall conductivity of each line while the TDR profile shows graphically the variations of



(a)



(b)

Fig. 3. Au sputtered P-FCB. (a) Chip pads by sputtering process. (b) Microphotograph of the surface 100 × magnified.

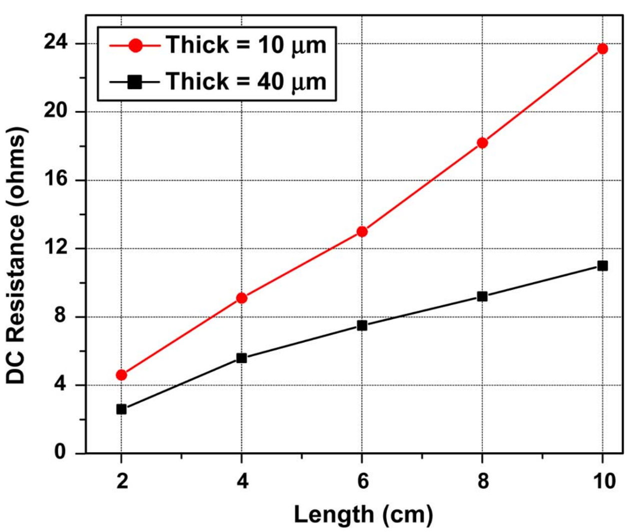


Fig. 4. DC resistance versus wire length and thickness.

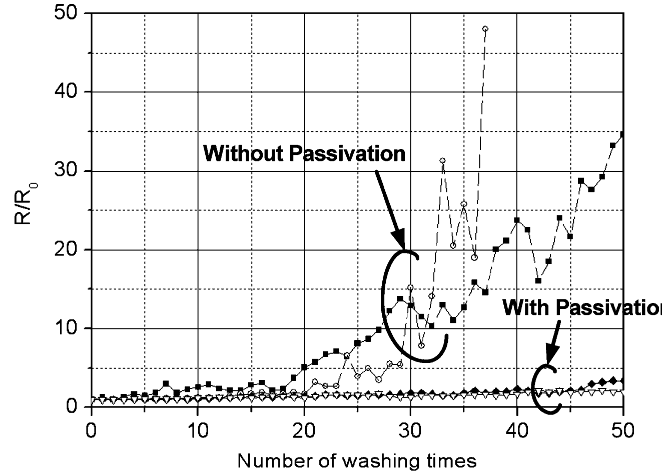


Fig. 5. Variance of resistance with washing.

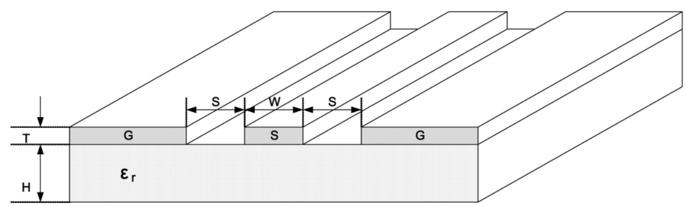


Fig. 6. Cross-section of GSG coplanar waveguide.

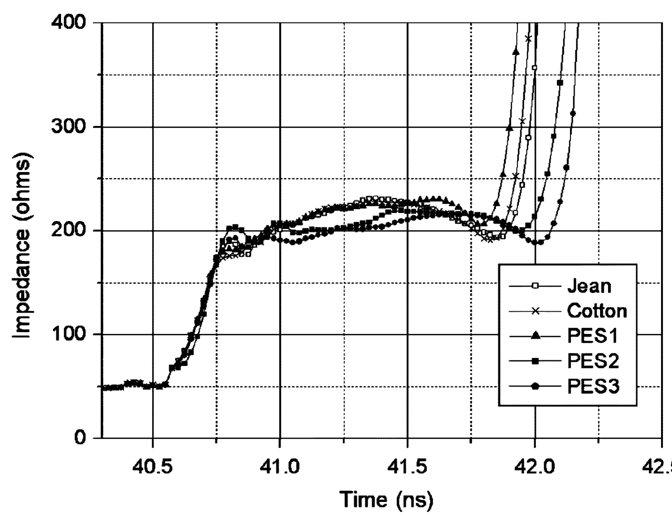


Fig. 7. TDR measurement of transmission lines.

impedance along the lines. To investigate the frequency characteristics, we measure the transmission properties with vector network analyzer (VNA) up to 3 GHz. In addition, the low frequency characteristics down to 100 MHz are measured in detail. The crosstalk between two neighboring signal lines is analyzed to check its signal isolation. In this study, all of the measurements are performed with the screen printing P-FCB. Table V summarizes the electrical characteristics of the fabric transmission line on P-FCB and its comparison with the previous works of conductive yarn technology and thick film on nonwoven substrates [6], [8], [16], and details will be explained below.

A. DC Resistance

The dc resistance of the film wire on PES fabric, type #3 of Table III, with width of 1 mm, length of 2 cm and thickness of 10 μm is measured as 4.6 Ω by the four-point probe technique [17]. The sheet resistance is 0.23 Ω/□. Like the general resistive wires, the dc resistance of the P-FCB is proportional to the length and inversely proportional to its width and thickness. The variation of resistance values in terms of the wire length and printing times is shown in Fig. 4.

In wearable computer applications, the washing endurance is very important to integrate electronic devices onto real clothes. Coating of the passivation materials, for example, polyurethane,

TABLE IV
EXTRACTED EQUIVALENT PARAMETERS

Parameters	Jeans	Cotton	PES #1	PES #2	PES #3
Line Impedance $Z_0\,(\Omega)$	210.11	209.65	214.81	207.62	201.81
Impedance Variation (%)	±12.9	±13.1	±11.4	±7.4	±8.8
Parallel Capacitance $C_p = \frac{t_d}{Z_0}$ (pF)	2.74	2.68	2.44	3.01	3.28
Series Inductance $L_s = t_d \cdot Z_0$ (nH)	120.8	117.9	112.8	129.8	133.7
Effective Permittivity $\varepsilon_{eff} = (\frac{t_d \cdot c}{l})^2$	1.32	1.26	1.10	1.56	1.75

TABLE V
COMPARISON WITH CONVENTIONAL FABRIC TRANSMISSION LINES

	[6] ETHZ, TOAP 2003	[8] ETHZ, TOAP 2007	[16] NCSU, 2005	This work
DC resistance (Ω/m)	17.05	17.2	20.75	13.35
Impedance (Ω)	263	295	130	201.81
Bandwidth (GHz)	1	1.8	-	0.08
Crosstalk (%)	7.2	-	-	5.6

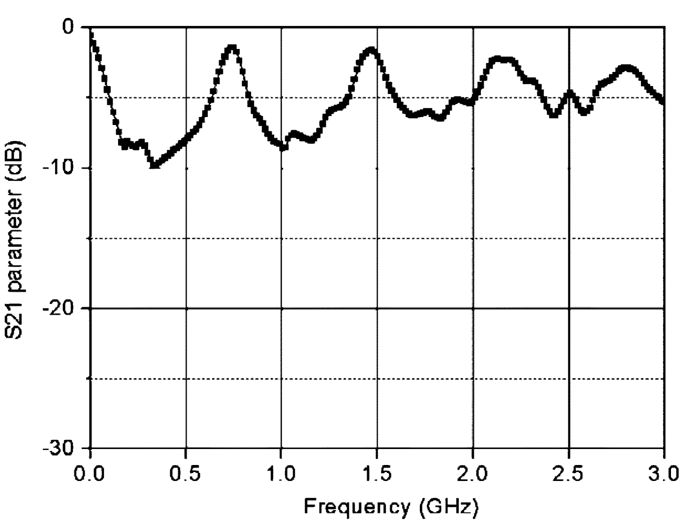


Fig. 8. Frequency response at high frequency.

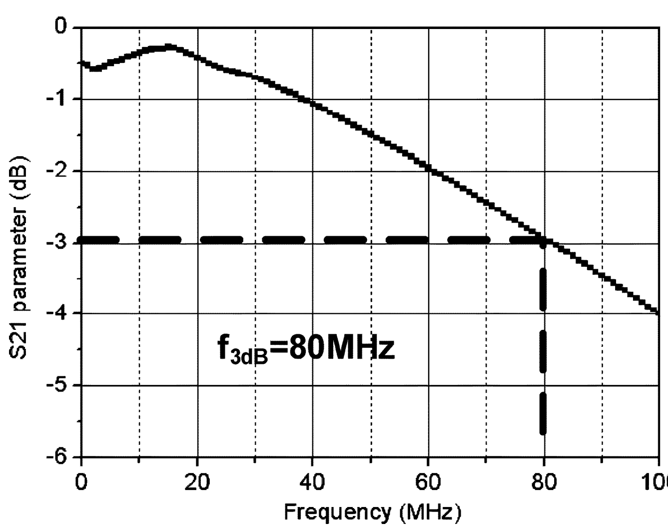


Fig. 9. Frequency response at low frequency.

can improve the endurance of the P-FCB against chemical and mechanical attacks like washing. Several tens of washing tests including dry cleaning and water-washing with the detergent are performed to the P-FCB fabrics. The samples without passivation experience thinning of its wire thickness or even the open connections, and their resistance values increase up to 40 times of its original value after about 20 washes. With the passivation material coated, their endurance against washings increases up, and the variation of the resistance values is less than 2 times of their original values after 50 washes, as shown in Fig. 5. This means that P-FCB degrades gracefully with time and usage in its performance exactly the same way as the clothes on which it is placed. That is to say, the P-FCB can be the integral part of the clothes and will be aged exactly the same as its hosting clothes.

B. AC Impedance Characterization

To investigate the ac impedance characteristics, coplanar waveguides (CPW) are formed on the fabric and are tested. The ground–signal–ground (GSG) CPW consists of a signal line paralleled by a pair of ground lines in each side on the same plane as illustrated in Fig. 6, [18]. We fabricate various configurations of the transmission lines such as one or two ground lines. The H, the thickness of dielectric substrate, i.e., fabric, is 100 μm and the T, thickness of the printed wire, is 10 μm. The W, line width, and the S, space between the signal line and the ground line, can be varied.

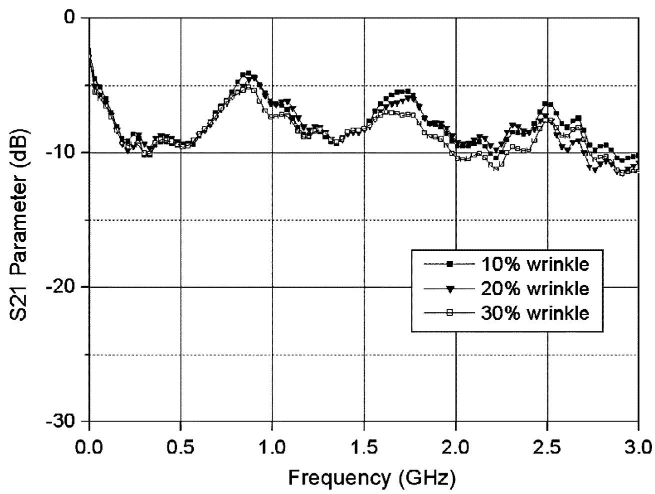


Fig. 10. Frequency response with wrinkle.

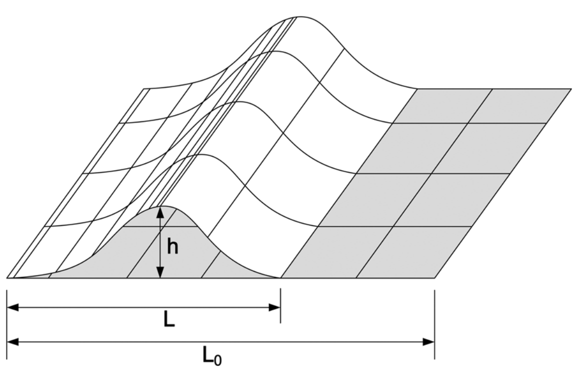


Fig. 11. Diagram of a wrinkled fabric.

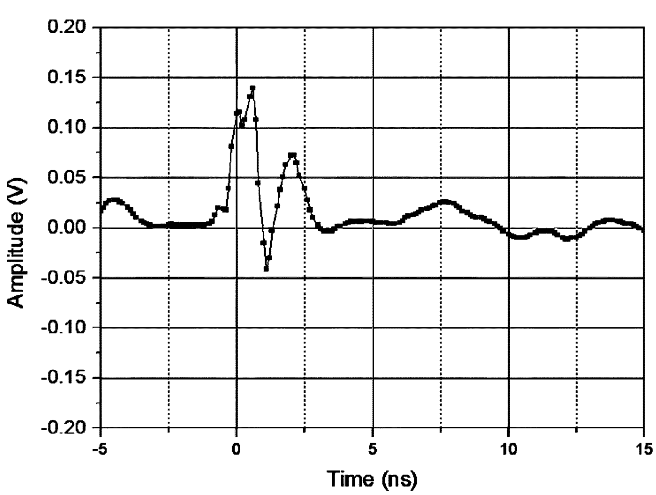


Fig. 12. Crosstalk between two signal lines.

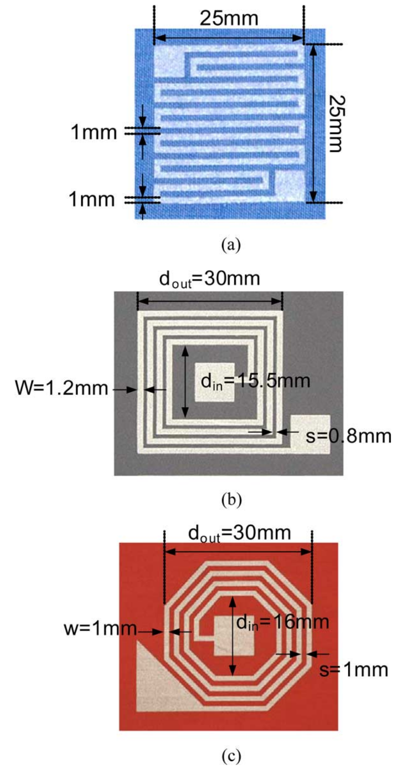


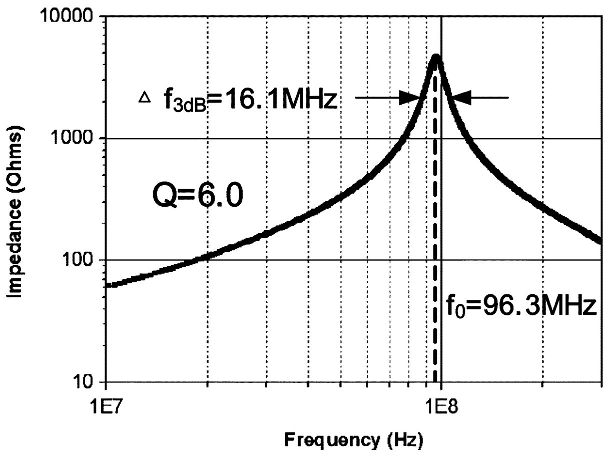
Fig. 13. Resistor and inductors. (a) Resistor ($R = 85\ \Omega$). (b) Square inductor ($L = 577$ nH at 10 MHz). (c) Octagonal Inductor ($L = 970$ nH at 10 MHz).

Frequency dependent impedance is measured with TDR using a Tektronix TDS 8000B. SMA connectors are soldered on the various kinds of the fabrics, and their measurement results are shown in Fig. 7. For the signal transmission, no impedance variation along the transmission line is more critical rather than the impedance value itself to avoid signal reflections. The variation of impedance along the transmission line on cotton fabric is measured as $<13.1\%$ and that on type #2 PES fabric in Table III is $<7.4\%$. The equivalent parallel capacitance C_p, for example, 3.28 pF for PES #3, and series inductance L_s, 133.7 nH for PES #3, of the sample transmission line with 15 cm length are obtained by using TDR signal propagation time t_d and the characteristic impedance Z_0. The extracted values including the relative effective permittivity $\varepsilon_{\mathrm{eff}}$ for various fabrics are listed in Table IV.

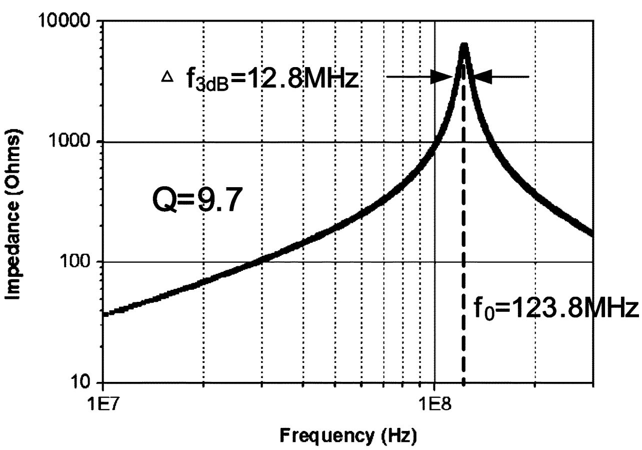
C. Frequency Characterization

S21 parameters for 15-cm-long lines are measured with vector network analyzer (VNA) up to 3 GHz to investigate the frequency characteristics of the transmission lines. The periodical attenuation shown in Fig. 8 comes from impedance mismatch along the transmission lines. Its bandwidth, defined as the frequency range from 0 Hz up to the first notch below -3 dB in the frequency response, is 80 MHz. The detail response of the transmission lines at a low frequency from 0 Hz to 100 MHz are also shown in Fig. 9.

To investigate the variation of the frequency responses with bending or twisting of clothes, S21 parameters of the transmission lines on a wrinkled fabric are measured, and its results are shown in Fig. 10. The percentage of wrinkle means the ratio of the length L of the wrinkled fabric to its original length L_0 as shown in Fig. 11. The effect of the wrinkle height h to the S21 is found negligible. Although 5 dB attenuation is observed at a high frequency of 3 GHz, the overall trend of the frequency characteristics is maintained the same as that without any wrinkles.



(a)



(b)

Fig. 14. Measured results of impedance variation of P-FCB inductors. (a) Square inductor. (b) Octagonal inductor.

D. Crosstalk

Fig. 12 shows the far-end crosstalk measurements between a signal line and a neighboring ground line with 15 cm length and terminated by a matched load. The amplitude of the aggressor signal is 2.5 V with a rise time of 6 ns. The space between two lines is 6 mm. As shown in Fig. 12, the noise signal on the victim wire is 0.14 V, or the crosstalk effect appears under 5.6%.

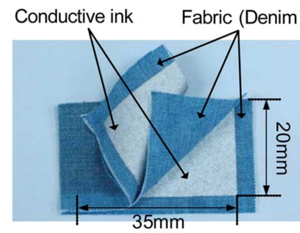
IV. Integrated Circuits on the Patterned Fabric

A. Resistors

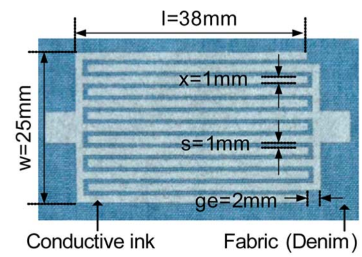
Passive electrical elements such as resistors, capacitors, and inductors can be fabricated on P-FCB, as shown in Fig. 13. The resistors can be implemented by long wires. A meandering wire of 300 mm with 1 mm width and 1 mm space, as shown in Fig. 13(a), behaves as a resistor of 85 Ω. An approximate formula for the resistance of a film wire is

$$R = \rho\left(\frac{L}{TW}\right) \tag{2}$$

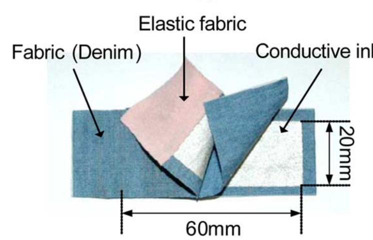
where L is the wire length, T is its thickness and W its width, and ρ is the resistivity of the film, in this case, $L = 300$ mm, $T = 10$ μm, $W = 1$ mm, and $\rho = 2.8 \times 10^{-6}$ $\Omega\cdot$ m. The sheet resistance is 0.28 $\Omega/\square$. The measured resistivity of the film wire is larger than 5.34×10^{-7} $\Omega\cdot$ m of the conductive paste and the mentioned sheet resistance due to the nonuniformity of the surface and the corners of the meandering wire. Of course, the resistivity can be modified with the screen printing inks by varying types of the conducting materials and their amount in the ink.



(a)



(b)



(c)

Fig. 15. Three types of capacitors. (a) Type-A. (b) Type-B. (c) Type-C.

B. Inductors

A planar spiral inductor can be fabricated on the fabric and its inductance value is given by (3) with the number of turns n, the turn width w, the turn spacing s, the outer diameter d_{out}, the inner diameter d_{in}, the average diameter $d_{\mathrm{avg}} = 0.5(d_{\mathrm{out}}+d_{\mathrm{in}})$, and the *fill ratio*, defined as $f = (d_{\mathrm{out}} - d_{\mathrm{in}})/(d_{\mathrm{out}} + d_{\mathrm{in}})$ [19]

$$L = K_1 \cdot \mu_0 \cdot \frac{n^2 \cdot d_{\mathrm{avg}}}{1 + K_2 f} \tag{3}$$

The coefficients K_1 and K_2 are dependent with the layout, that is, $K_1 = 2.34$ and $K_2 = 2.75$ for squares, and $K_1 = 2.25$ and $K_2 = 3.55$ for octagonal inductors. Fig. 13(b) and (c) shows a square inductor on P-FCB with $n = 4$, $w = 1.2$mm, $s = 0.8$ mm, $d_{\mathrm{out}} = 30$ mm, $d_{\mathrm{in}} = 15.5$ mm, $d_{\mathrm{avg}} = 22.75$ mm and $f = 0.32$ and an octagonal inductor with $n = 4$, $w = 1$ mm, $s = 1$ mm, $d_{\mathrm{out}} = 30$ mm, $d_{\mathrm{in}} = 16$ mm, $d_{\mathrm{avg}} = 23$ mm, and $f = 0.3$. Their impedance variations with respect to the frequency are reported in Fig. 14 and their measured inductance values are 577 nH with $Q = 6.0$ at 10 MHz and 970 nH with $Q = 9.7$ at 10 MHz, respectively. Measured Q factors are quite

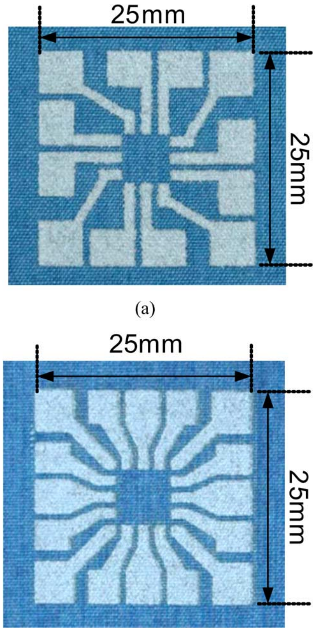


Fig. 16. Lead frames. (a) 12 pin. (b) 16 pin.

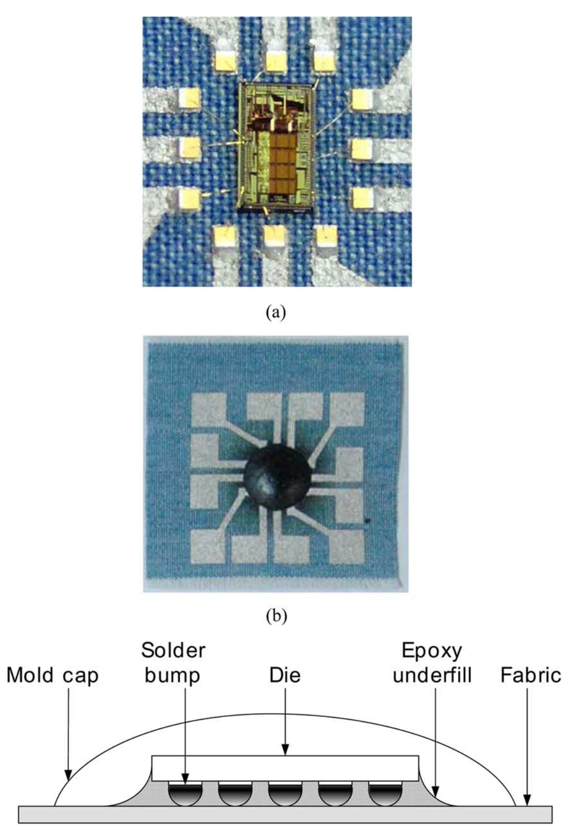


Fig. 17. Bonding and packaging on the fabric. (a) SoC on P-FCB. (b) Molded package. (c) Diagram of a flip-chip package.

small due to their planar spiral structures and large resistances. To obtain larger inductance value, it needs further optimization.

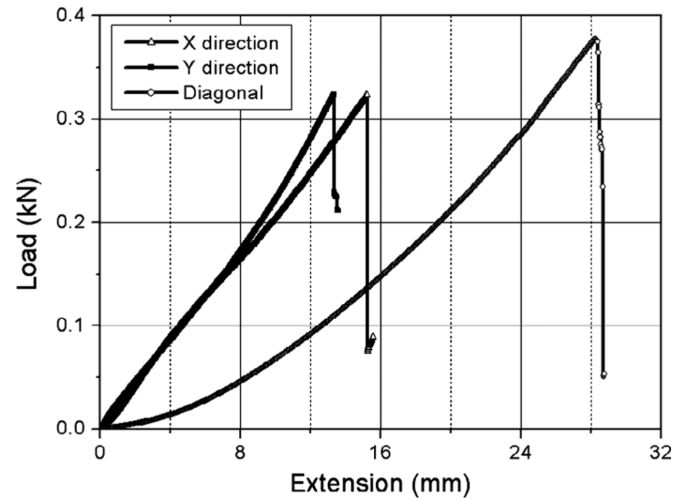


Fig. 18. Tensile strength test with three direction.

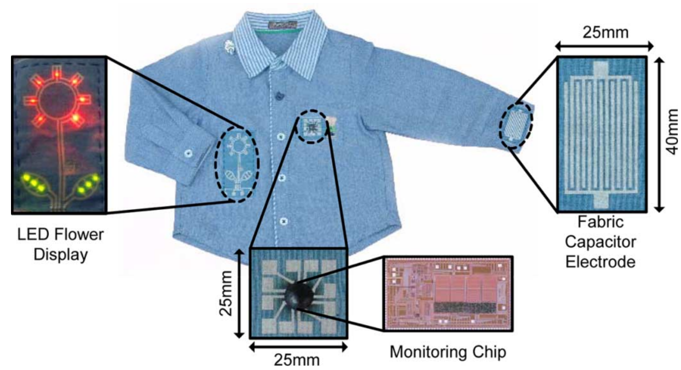


Fig. 19. System integration on P-FCB with capacitive sensor, chip and LED display.

C. Capacitors

Three types of capacitors on the fabric are investigated as shown in Fig. 15. The type-A capacitor of Fig. 15(a) is a simple two parallel-plate capacitor. Its capacitance value can be found with the well known parallel capacitor formulation of

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \tag{4}$$

where ε_r is the relative permittivity of the medium, ε_0 is the permittivity of free space, A is the plate area, and d is the separation between the plates. The capacitance value with A of 35×20 mm^2 and the denim fabric of 320 μm thickness is 50 pF. When it is pushed from the top to the bottom, two outer electrodes get closer to each other due to the flexibility of the medium fabric to increase its capacitance value. Therefore, the type-A capacitor can be used as a variable capacitor to detect the pressure.

The Fig. 15(b) shows the type-B interdigitated capacitor. Its design variables are the number of fingers n, finger length l, finger width x, finger gap s, end gap ge, terminal width w, substrate height h, substrate thickness t, and dielectric constant of the fabric. Its capacitance value is expressed as follows [20]:

$$C = \frac{(\varepsilon_r \varepsilon_0 + 1)}{d} l[A_1(n-3) + A_2] \tag{5}$$

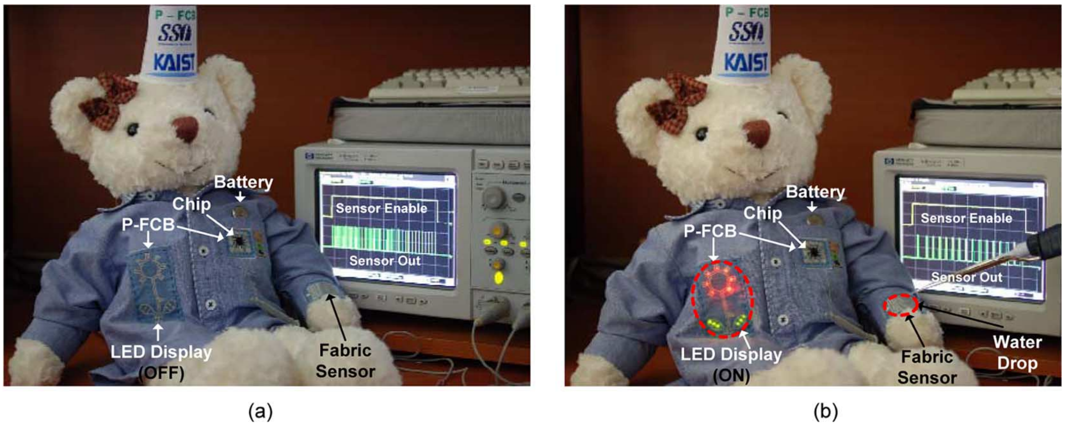


Fig. 20. Photograph of the test measurement setup and measurement results. (a) LED off. (b) LED light-on with water drop on the sensor.

where A_1 and A_2 represent the contribution of the interior and two exterior fingers, respectively, and their values are a function of (t/x). The type B capacitor of Fig. 15(b) with $n = 6$, $l =$ 38 mm $x = 1$ mm, $s = 1$ mm, $\mathrm{ge} = 2$ mm, $w = 25$ mm, $h = 320 \mu$m, $\varepsilon_r = 4.0$, and 40×25 mm^2 denim fabric patch is 10 pF.

The type-C capacitor of Fig. 15(c) can be fabricated in the same way as type-A, but in addition, it has elastic fabrics at both sides, and when it is stretched horizontally, the overlap areas or the capacitance values can be varied. This type of capacitor can detect the horizontal force on the fabric. The capacitance value of Type-C capacitor with two 60×20 mm^2 planar electrodes can vary from 10 to 100 pF.

D. Direct Bonding and Packaging of Silicon Chip on Fabric

Fig. 16 shows the lead frames fabricated on the fabric with 12 pads and 16 pads. The width of the leads is limited to 1 mm for the reliability of the silk screen process. The SoC chip can be bonded and packaged directly on the fabric lead frame as shown in Fig. 17. In conventional conductive yarn approaches, the pitch mismatch between the IC pads and the yarns requires an interposer between the chip and the fabric. This extra process increases the cost and hardness mismatch. On the other hand, in the P-FCB, arbitrary shape of lead frame can be implemented to optimize the integration of silicon chip onto the fabrics. First, the chip is attached on the P-FCB lead frame with glue. Then, gold wire is bonded on the pads of the chip, and next, it is bonded to the lead frame on the P-FCB. Instead of the SoC chip, chip capacitors, resistors, LEDs, or any other elements can be mounted on P-FCB of course. The dimension of the molded package is 1 cm $\times$ 1 cm, and the height is 2.2–2.5 mm which is small enough to make it unrecognizable and comfortable to wear. Of course the flip-chip bonding can be used on P-FCB. In the final wafer processing step, the solder bumps are deposited on the chip pads and then, the chip is inverted to face the solder bumps down onto the lead frame on the underlying fabric. The solder is then remelted to make electrical connections, typically using an ultrasonic process [21].

Liquid molding epoxy is coated on the chip after bonding process. This molding process provides highly robust protection against potential pressure on the packaged chip. For the integrity of the package with the fabrics, the tensile strength test is performed by straining the P-FCB along the x-direction, y-direction, and the diagonal directionn. In every experiment, the fabrics are torn before the bonding or package is broken. The maximum load is 85.1 N/cm in the x-direction, 85.2 N/cm in the y-direction and 99.3 N/cm in the diagonal direction as shown in Fig. 18. Total strain in the x-direction is 19.5%, the y-direction 27.2%, and the diagonal direction 26.8%, respectively.

V. System Integration on the Fabric Circuit

The P-FCB technology is applied to implement a complete system for continuous healthcare [9]. It is composed of a fabric capacitive sensor, a controller SoC chip including the capacitive sensing circuit, and an LED array display as shown in Fig. 19. The capacitive sensor is fabricated in the type-B capacitor of Section IV. Its number of fingers $n = 10$, finger length $l = 38$ mm, finger width $x = 1$ mm, finger gap $s = 1$ mm, end gap $\mathrm{ge} = 1$ mm, terminal width $w = 5$ mm, and substrate height $h = 100$ μm, and its capacitance value is 1 pF. The supply voltage line and ground line with LED array connected between them are formed in the shape of a flower for the purpose of display, and chip resistors are surface mounted. The controller SoC is integrated on the P-FCB lead frame through the bonding and molding process of Section IV. The lead frame has 12-pin pads. Each module of the sensor, the display, the controller, and a battery is electrically connected by sewing of the conductive yarns on the fabric. All measurements are conducted on wearable system as shown in Fig. 20. The humidity has a great effect on the capacitance values of all types of capacitors, which was well known by Ong's study [22]. The capacitance value goes up when humidity increases. Without a water drop, the number of the pulses of Fig. 20(a) is 34 or equivalent to 200 pF. When a water drop is detected by fabric sensor electrode, the controller chip senses the variation of the capacitance value. Then, the LED light is on when the capacitance value is over the programmed threshold value and the number of pulses decrease to 4 or equivalent to 1 nF, as shown in Fig. 20(b).

VI. Conclusion

This paper proposes, for the first time, planar circuit printing technology for the formation of the electronic circuit board and direct integration of silicon chips on the fabric. The thick film process, screen printing, and thin film process, sputtering deposition, are used in manufacturing P-FCB. After investigation of electrical properties of some textile materials, the polyester fabric with fine yarn and high density is selected for its low resistance of wire and relatively high stability of connection. The thickness of the fabric substrate is 100 μm and that of conductive wire is 10 μm.

For the extensive characterization of textile transmission lines on P-FCB, we extract the dc resistance, TDR profile, and frequency characterization. TDR measurements show that the characteristic impedances are between 180 Ω and 230 Ω. High-frequency network analyzer measurements were performed up to 3 GHz for high-frequency behavior and down to 100 MHz for low-frequency behavior. Reliable signal transmission for 80 MHz clock signal was observed along 15 cm textile lines. The experiments show that the variation of insertion loss is limited in 1.2 dB with fabric wrinkle.

Various types of electric elements, such as resistors, capacitors, and inductors are fabricated and experimental formulae to calculate their values are obtained. Lead frames with 12-pin or 16-pin pads are fabricated for the chip integration. A SoC chip is wire-bonded on the lead frames directly and the packaging process is performed on the chip in the same way as the IC industry. With the molded package, P-FCB provides high mechanical endurance against any directional pressure on clothes.

Finally, a system with a capacitive sensor, an LED array display, and a SoC controller is assembled on P-FCB and its operation is demonstrated successfully. Potentially, the P-FCB system will open up a new solution to the healthcare area by allowing people to monitor their health condition just by wearing clothes with the P-FCB system.

REFERENCES

[1] S. Jung, C. Lauterbach, M. Strasser, and W. Weber, "Enabling technologies for disappearing electronics in smart textiles," in *ISSCC Dig. Tech. Papers*, Feb. 2003, vol. 1, pp. 386–387.

[2] D. Marculescu *et al.*, "Electronic textiles: A platform for pervasive computing," *Proc. IEEE*, vol. 91, no. 12, pp. 1995–2018, Dec. 2003.

[3] S. Park, K. Mackenzie, and S. Jayaraman, "The wearable motherboard: A framework for personalized mobile information processing (PMIP)," in *Proc. Design Automat. Conf.*, Jun. 2002, pp. 170–174.

[4] E. Post, M. Orth, P. Russo, and N. Gershenfeld, "E-broidery: Design and fabrication of textile-based computing," *IBM Syst. J.*, vol. 39, pp. 840–860, 2000.

[5] J. Edmison, M. Jones, Z. Nakad, and T. Martin, "Using piezoelectric materials for wearable electronic textile," in *Proc. Int. Symp. Wearable Comput.*, Oct. 2002, pp. 41–48.

[6] D. Cottet, J. Grzyb, T. Kirstein, and G. Trster, "Electrical characterization of textile transmission lines," *IEEE Trans. Adv. Packag.*, vol. 26, no. 2, pp. 182–190, May 2003.

[7] S. Jung, C. Lauterbach, and W. Weber, "A digital music player tailored for smart textiles: First results," in *Proc. Avantex Symp.*, 2002, p. 15.

[8] I. Locher and G. Trster, "Fundamental building blocks for circuits on textiles," *IEEE Trans. Adv. Packag.*, vol. 30, no. 3, pp. 541–550, Aug. 2007.

[9] H. Kim, Y. Kim, Y. Kwon, and H. Yoo, "A 1.12 mW continuous healthcare monitor chip integrated on a planar-fashionable circuit board," in *ISSCC Dig. Tech. Papers*, Feb. 2008, pp. 150–151.

[10] C. Coombs, *Printed Circuits Handbook*, 6th ed. New York: McGraw-Hill, Aug. 2001.

[11] K. Asanovic *et al.*, "Investigation of the electrical behavior of some textile materials," *J. Electrostat.*, vol. 65, pp. 162–167, 2007.

[12] P. Berberi, "Effect of processing on electrical resistivity of textile fibers," *J. Electrostat.*, vol. 51, pp. 538–544, 2001.

[13] W. Morton and J. Hearle, "Physical properties of textile fibers," *Textile Inst.*, pp. 216–302, Apr. 1993.

[14] S. Bibikov, E. Kulikovskij, and A. Mareychev, "Radiotechnical properties of metalized fabrics," in *Proc. 5th Int. Conf. Antenna Theory Tech.*, May 2005, pp. 508–511.

[15] P. Holmes and R. Loasby, *Handbook of Thick Film Technology*. UK: Electrochemical, 1976.

[16] C. Merritt *et al.*, "Electrical characterization of transmission lines on nonwoven textile substrates," in *MRS Spring Meeting Symp.*, San Francisco, CA, Mar. 2005, vol. 870E.

[17] C. Petersen *et al.*, "Scanning microscopic four-point conductivity probes," *Sensors Actuators*, vol. 96, no. 1, pp. 53–58, Jan. 2002.

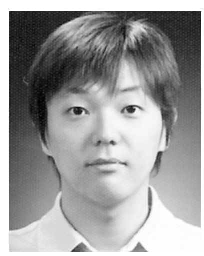
[18] R. Simons, *Coplanar Waveguide Circuits, Components and Systems*. New York: Wiley-IEEE Press, 2001.

[19] S. Mohan, M. Hershenson, S. Boyd, and T. Lee, "Simple accurate expressions for planar spiral inductances," *IEEE J. Solid-State Circuits*, vol. 34, no. 10, pp. 1419–1424, Oct. 1999.

[20] G. Alley, "Interdigital capacitors and their application to lumped-element microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 18, no. 12, pp. 1028–1033, Dec. 1970.

[21] C. Harper, *Electronic Packaging and Interconnection Handbook*, 4th ed. New York: McGraw-Hill, 2004.

[22] K. Ong, C. Grimes, C. Robbins, and R. Singh, "Design and application of a wireless, passive, resonant-circuit environmental monitoring sensor," *Sensors Actuators A: Phys.*, vol. 93, no. 1, pp. 33–43, Aug. 2001.



Yongsang Kim (S'07) received the B.S. degree in electrical engineering, in 2004, from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, where he is currently working toward the M.S. degree in the same department.

His research includes printing circuit board techniques on the fabric and low power sensor unit design for wearable computer system.

Hyejung Kim (M'04) received the B.S., M.S., and Ph.D. degrees from KAIST, Daejeon, Korea, in 2004, 2006, and 2009, respectively.

During the period in KAIST, she developed low-energy biomedical signal processors. Her research includes SoC design for the continuous wearable ECG monitoring system and its implementations. She is currently working at IMEC as a Postdoctoral Researcher.

Hoi-Jun Yoo (F'08) graduated from the Electronic Department of Seoul National University, Seoul, Korea, in 1983, and received the M.S. and Ph.D. degrees in Department of Electrical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, in 1985 and 1988, respectively. His Ph.D. work concerned the fabrication process for GaAs vertical optoelectronic integrated circuits.

From 1988 to 1990, he was with Bell Communications Research, Red Bank, and in 1991, he became a manager of the DRAM design group at Hyundai Electronics. In 1998, he joined the faculty of the Department of Electrical Engineering at KAIST and now is a full professor. From 2003 to 2005, he was the full-time Advisor to Minister of Korea Ministry of Information and Communication and National Project Manager for SoC and Computer. His current interests are high-speed and low-power Network on Chips, 3-D graphics, Body Area Networks, biomedical devices and circuits, and memory circuits and systems.