

Research Article

Electrical Properties of Horizontal Array Capacitor Using Composite Organic Dielectric Layer of Impregnated Glass-Fiber Epoxy

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Received 15 October 2019; Revised 2 January 2020; Accepted 13 January 2020; Published 27 April 2020

Guest Editor: Yiju Li

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We introduce a horizontal array capacitor with nine capacitances in a single body using an organic dielectric layer impregnated with glass fiber as a prepreg sheet. An organic solid horizontal array capacitor with a dielectric of prepreg materials of the epoxy type can implement the nine capacitances in a single body via a unique simple lamination and cutting process. We then investigate the basic electrical properties of a horizontal array capacitor. The organic solid array capacitors with five electrodes and four dielectrics are Cu/PPG layer/Cu/PPG layer/Cu/PPG layer/Cu/PPG layer/Cu with a horizontal array structure. The size of a completed array capacitor is 2.85×2.85 mm. The height of the fabricated array capacitor in the vertical direction is 0.5 mm, with nine capacitances possessing a series-type structure. The average capacitance value of C_1 , C_2 , C_3 , and C_4 is 1.98 nF, and each tolerance has a value within 1% based on the average value. The temperature change rate in the capacitance maintains a nearly linear characteristic, but the rate of change tends to increase finely from 120°C or more. The capacitance values of C_5 , C_6 , and C_7 with the parallel circuit were measured according to the voltage. Impedance and ESR (equivalent series resistor) of C_1 were measured according to frequency and temperature.

1. Introduction

TDK CKC series capacitor arrays offer multiple multilayer ceramic chip capacitors (MLCCs) in a single package. TDK's unique design offers low crosstalk to truly yield separate individual capacitors in a 100 nF single package. The array types are configured in 2-in-1 and 4-in-1 package styles [1]. SEMCO produce capacitor array (CAP, 100 nF, 16V, $\pm 20\%$, X7R, 0805) has 2-in-1 and 4-in-1 package styles [2]. Array capacitors consist of multiple capacitors in a single body and are effective in reducing the time and cost of placement and circuit space. Several other companies also produce array-capacitors. The dielectrics in the array capacitor used

here are fabricated from ceramic materials. Typically, ceramic loading, which is used as a dielectric, should be much lower than 50 vol% to successfully pass the high-temperature thermal stress reliability test. The dielectric properties of polymer-ceramic composites for embedded capacitors have been presented in a study on the optimization of ceramic-polymer films at a ceramic loading of 40 vol% to improve the embedded capacitance tolerance and electrical properties [3–5]. The effects of BaTiO₃ powder on ceramic-polymer films and MLCC using the BaTiO₃-based oxides have been widely adopted in the dielectric materials for various electronic components [6–9]. In this study, a research study is introduced wherein array capacitors are constructed using

organic-type PPG (prepreg) instead of ceramic materials such as BaTiO₃. Prepreg is an intermediate material for high-strength composites and is often used in sheet form. It is composed of a molding material impregnated with epoxy resin (MATRIX), specially mixed with reinforcing material carbon fiber, glass fiber, and aramid fiber, among others. High-strength, high-elasticity, and ultra-lightweight features are widely applied to sports, leisure, aerospace, automobile, robotics, and other fields that require high-performance materials. Prepreg-type epoxy is a superior material, with properties such as low weight, high strength, thermal shock resistance, excellent dimensional stability at high temperature, low coefficient of thermal expansion (CTE), chemical resistance, and corrosion resistance, compared to general organic-type epoxy [10–12]. The impregnated glass-fiber epoxy uses the energy-storing structures to make the composite capacitors and batteries [13]. PPG using GCU explored the preparation of glass fiber coir-reinforced unsaturated polyester resin hybrid (GCU) composites with a novel prepreg/press fabrication process. Flexural, impact, and thermomechanical properties of GCU composites were investigated [14]. Recently, various properties such as CNT were added to glass-fiber epoxy to measure the temperature characteristics [15].

We studied the fundamental properties of capacitances of the 6-in-1 array-type in a single body using only organic dielectrics in a previously published paper [16]. In this study, we introduce the temperature and RF characteristics of a horizontal array-type capacitor (9-in-1) with 9ea capacitance using an organic dielectric of a prepreg material instead of a dielectric prepared with conventional BaTiO₃ powder. This study aims to confirm the applicability of this material to array capacitors based on the results obtained through the basic structure and experiments using a composite organic dielectric layer of impregnated glass-fiber epoxy. Consequently, array capacitors with a composite organic dielectric of prepreg can be applied to various electronic circuits to demonstrate the possibility of reducing the module size.

First, Figure 1 is the structure of a conventional ceramic array capacitor (MLLC) with four capacitors.

The cross section is composed of internal electrode (Ni), ceramic dielectric (BaTiO₃), and external electrode (Cu/Ni/Sn). To increase the reliability ensuring the high capacitance in MLCCs, Ni electrodes with uniformity are very important. Consequently, homogeneous and continuous Ni electrode and dielectric layers could enable the high-voltage operation suppressing the leakage currents, dielectric breakdown, and degradation. In fabricating the MLCCs with high reliability, high density of BaTiO₃ ceramic and continuous Ni electrode should be fulfilled simultaneously. To promote densification of BaTiO₃-based MLCCs, nanoparticles were utilized or composition of BaTiO₃ was intentionally modified with doping elements [17, 18].

In this study, the horizontal array capacitors with nine capacitances in a single body can be explained with the illustration in Figure 2. It consists of a series-type array structure of Cu/PPG layer/Cu/PPG layer/Cu/PPG layer/Cu/PPG layer/Cu connected to each other. It can have the structure of nine array capacitors, as shown in the following equation:

$$\begin{aligned}
 & C_1, C_2, C_3, C_4, \\
 & \frac{1}{C_5} = \frac{1}{C_1} + \frac{1}{C_2}, \\
 & \frac{1}{C_6} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}, \\
 & \frac{1}{C_7} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4}, \\
 & \frac{1}{C_8} = \frac{1}{C_2} + \frac{1}{C_3}, \\
 & \frac{1}{C_9} = \frac{1}{C_3} + \frac{1}{C_4}.
 \end{aligned} \tag{1}$$

Array capacitors with 9ea capacitance in a single body comprise five electrodes and four dielectrics, and the organic dielectric made of PPG materials between the metal (Cu) and metal (Cu) can form a capacitance. The capacitance between points A–B, B–C, C–D, D–E, H–J, H–K, H–L, I–K, and J–L are C₁, C₂, C₃, C₄, C₅, C₆, C₇, C₈, and C₉, respectively. If the organic dielectric material and thickness are made constant, the capacitance values of C₁, C₂, C₃, and C₄ will be the same. C₅ will have a series capacitance from C₁ and C₂, electrically connected in the series type as equation (1). C₆ can obtain a series capacitance value from C₁, C₂, and C₃ by electrically serial structures, as shown in equation (1). C₇, C₈, and C₉ can also be calculated using equation (1), as shown Figure 2. As we know, if the capacitors have an electrically series-type structure, the series capacitance value will be proportionally reduced using equation (1).

The implementation of the proposed horizontal array capacitor has several useful advantages if applied to an electronic circuit as shown in Table 1. First, it can reduce the size of the connection length and volume of the electronic circuit if several capacitors are configured in a single body. The reduced size of the electronic circuit can reduce the impedance value in a high-frequency environment. Second, if the capacitance value in the proposed array capacitor can be freely formed between electrodes, the serial and parallel circuits can be formed very easily. In this study, we proposed a unique solid array capacitor that can realize 9ea capacitance values in a single body through the structure background shown in Figure 1. Additionally, the experimental samples were prepared using a novel fabrication process and their electrical characteristics, such as voltage, temperature, and frequency, were analyzed.

2. Experimental Method

As shown in Figure 3, array capacitors with a series-type structure using PPG sheet in the horizontal direction can be manufactured as follows:

- (1) The PPG used in this study serves as a dielectric layer in the capacitor, whose less thickness indicates a large capacitance value. A PPG sheet, a molding material impregnated with a specially

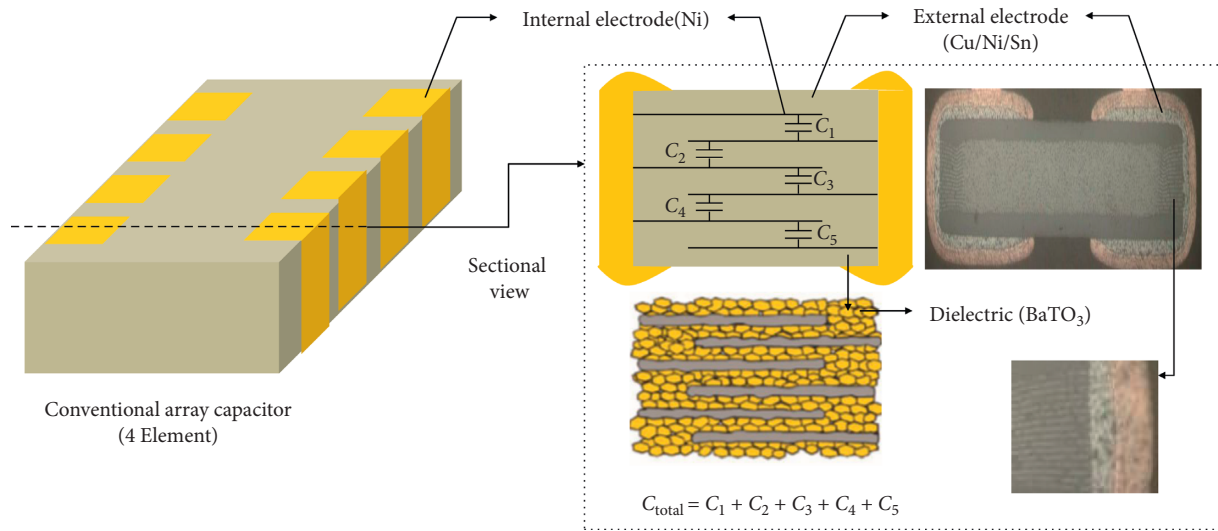


FIGURE 1: The structure of the conventional array capacitor.

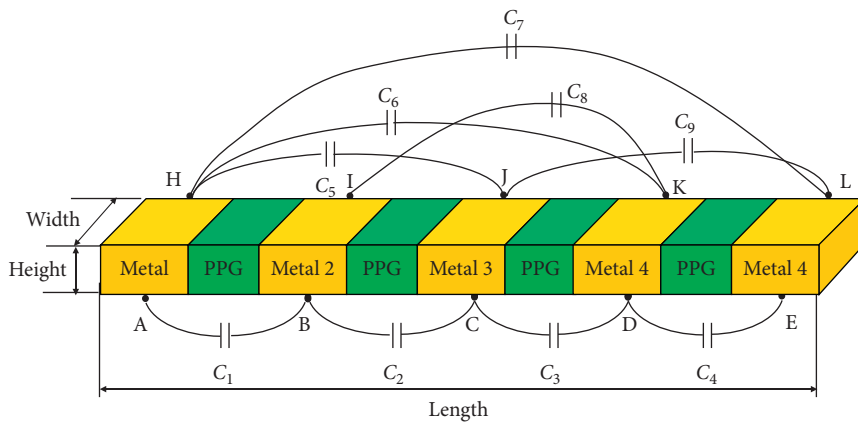


FIGURE 2: Application example of a horizontal array capacitor with 6 capacitors in single bodies.

TABLE 1: The example of the decoupling capacitor using the structure shown in Figure 1.

The proposed array capacitor	Ground position	The example of circuit schematic			
		1 point	2 points	3 points	4 points
	In case of ground 4				—
	In case of ground 2		—		
	In case of ground 2				
	In case of ground 2				
	No ground (parallel)				

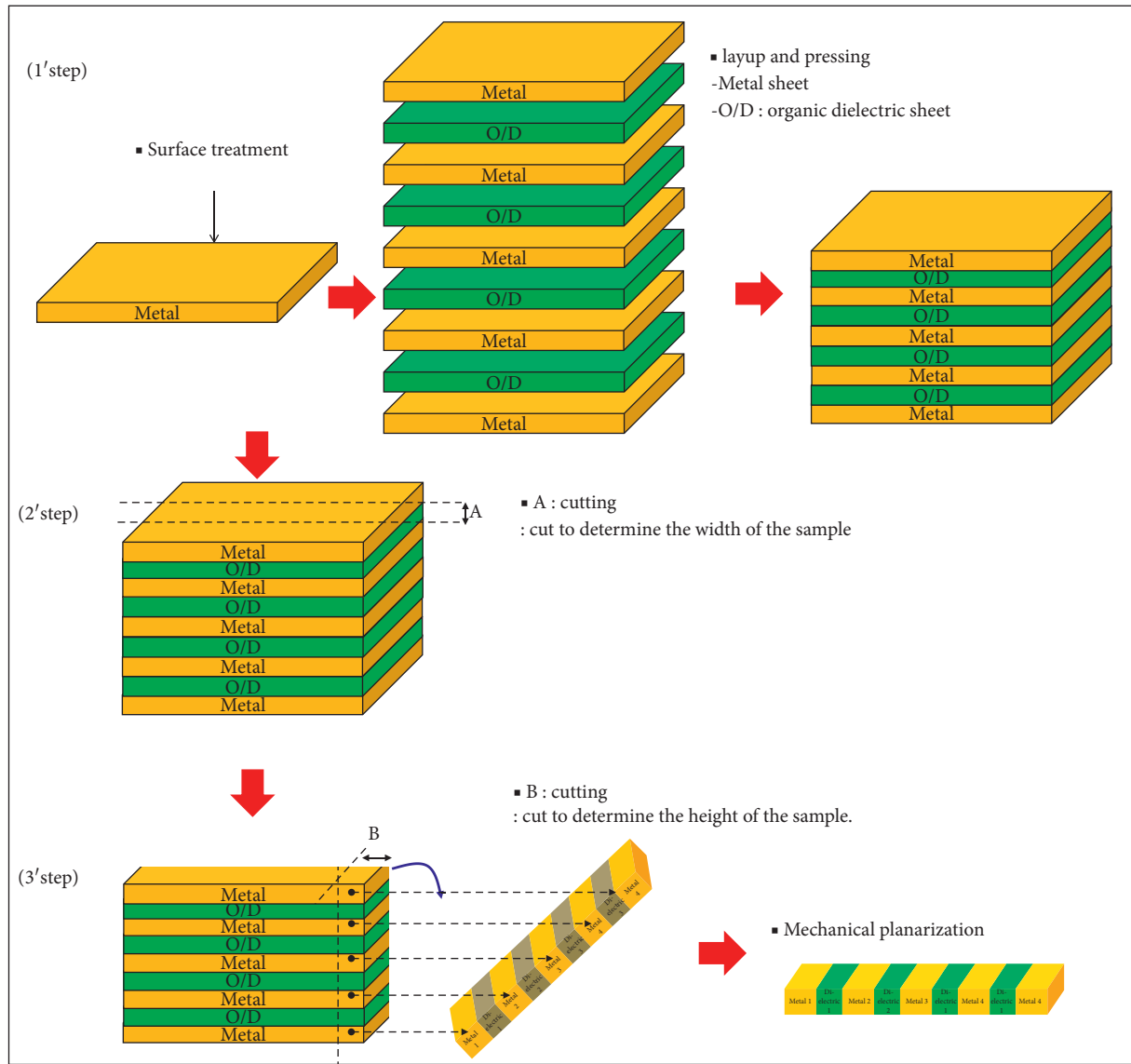


FIGURE 3: The fabrication method of the horizontal array capacitor with the PPG dielectric layer.

blended epoxy, and glass-fiber resin with a thickness of $60\ \mu\text{m}$ was used to form a dielectric layer between the Cu electrodes. PPG can be used as a dielectric material in a capacitor owing to its high strength, heat shock resistance, low CTE, chemical resistance, and corrosion resistance. Sheets with dimensions $100 \times 100\ \text{mm}$ were formed between the Cu electrodes. The PPG sheet was laminated using the pressure/time/temperature of the equipment, simultaneously, and a pressed PPG sheet was formed with an approximate thickness of $50\ \mu\text{m}$ between the two Cu sheets. The PPG sheet contains the epoxy of the B stage (impregnated glass fiber). It has a resin flow of less than 2.5 mm and 65% content. During the lamination process, some amount of epoxy resin fell out and the resulting thickness was reduced to approximately $50\ \mu\text{m}$.

It is halogen-free, produces very low dust in the punching and cutting process, has low CTE in the Z-axis, and high solder ability. Currently, the dielectric constant of this material is approximately 4.5~6.9 at low frequency. PPG sheet materials should be developed to have excellent electrical properties, stable temperature characteristics, and high capacity at high frequencies.

- (2) The top and bottom of the Cu sheet were cleaned. After laying down five Cu and four PPG sheets in order, they were pressed simultaneously using the lamination profiles (1' step).
- (3) He pressed samples were cut using a mechanical diamond cutter for the predesigned size vertically by 2'~3' steps.
- (4) The width of the proposed array capacitor was determined by the 2' step process, as illustrated in

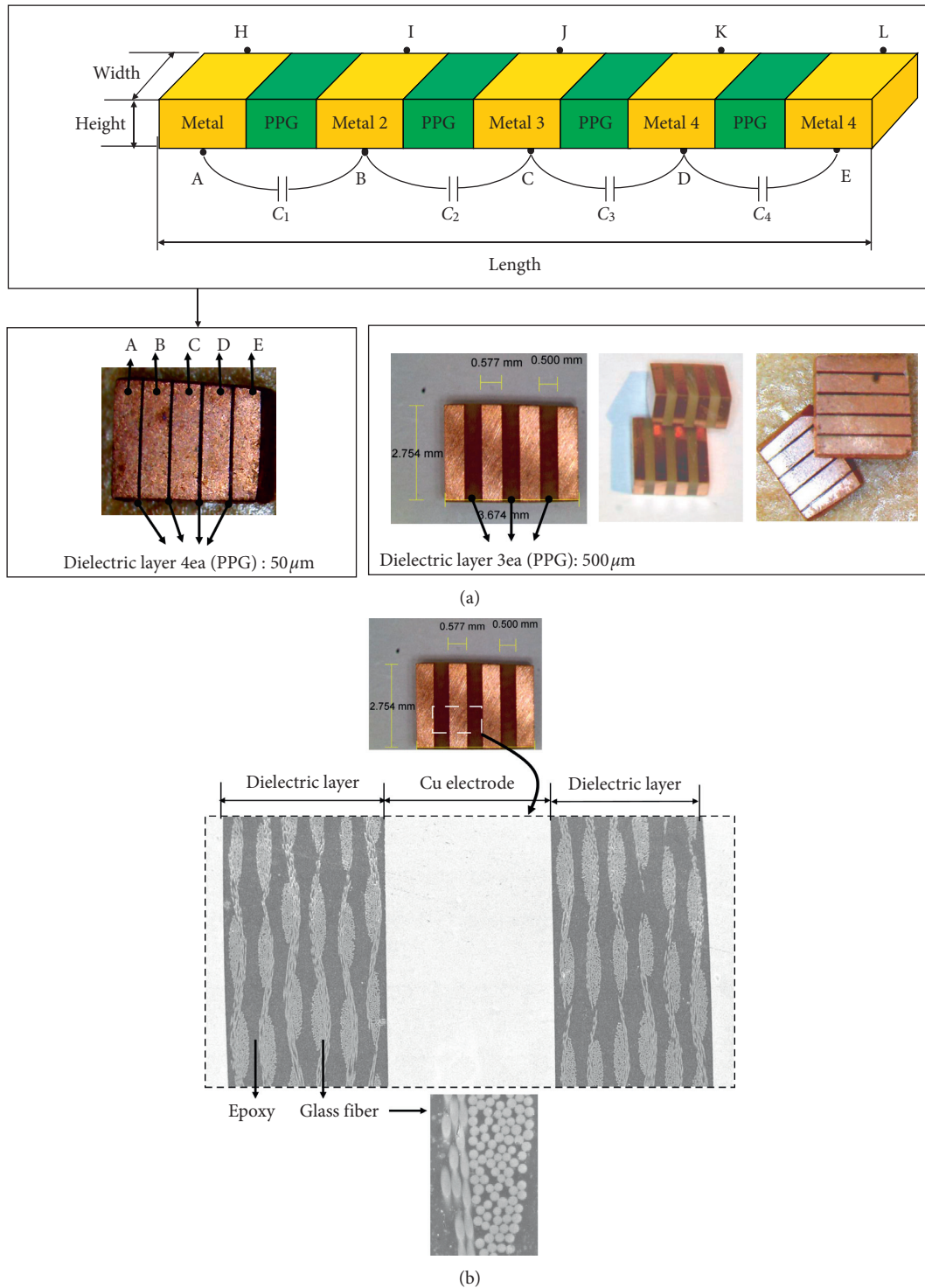


FIGURE 4: Fabricated horizontal array capacitor having (a) 9ea capacitances with five electrodes and four dielectrics and (b) an impregnated glass fiber of the epoxy as the dielectric.

Figure 3. First, it was cut to the size of a pre-designed width. The sample prepared by the cutting process should be again cut through the 3rd-step cutting process. The 3rd-step process was conducted to determine the height using the pre-designed size. After cutting, the sample was tilted sideways and

placed on the floor. The array capacitor with nine capacitances, consisting of five electrodes and four dielectrics, can be fabricated using the sequence of the new process, as described above. The cut sample was finished using a mechanical flattening operation.

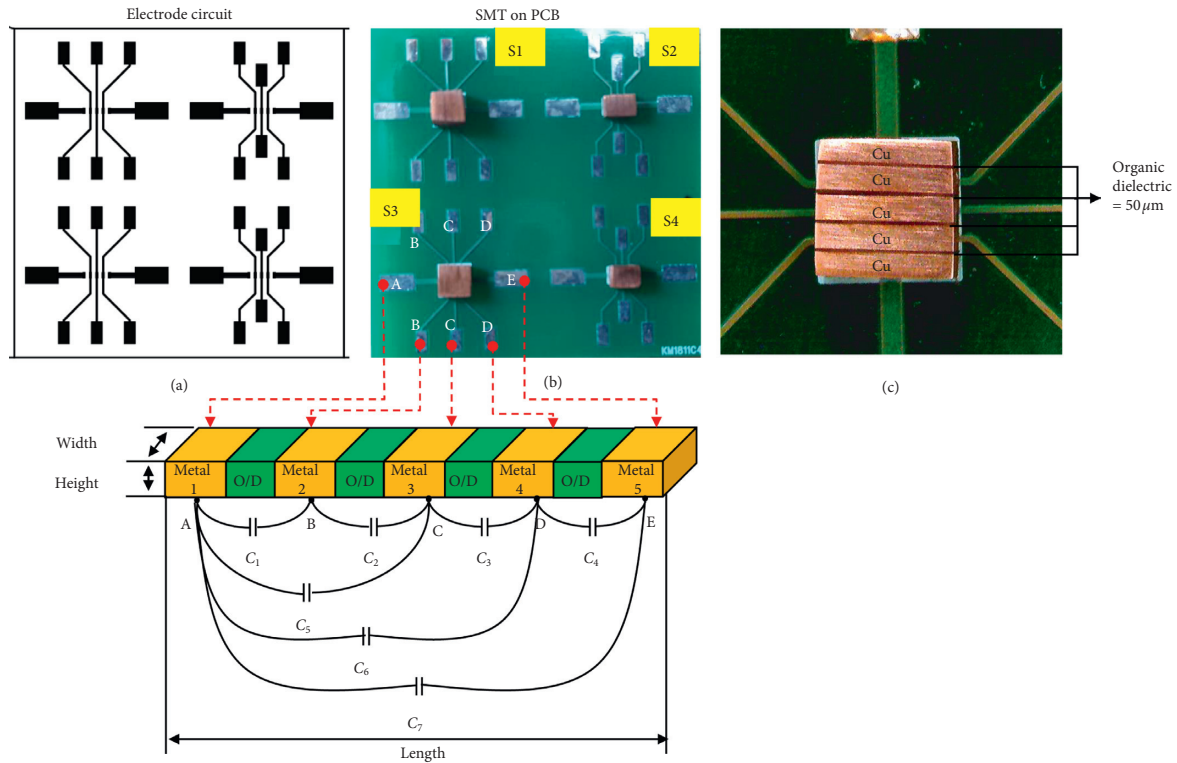


FIGURE 5: SMT of array capacitors on the PCB to measure the electrical properties.

Figure 4(a) illustrates a flat photo of a unique array capacitor fabricated using five electrodes and four dielectrics. A fabricated capacitor has a size of sample 1 (2.754×3.674 mm) with four electrodes and three dielectrics and sample 2 (2.85×2.85 m) has five electrodes and four dielectrics. The thickness of the electrode and dielectric at the plane is approximately 0.5 mm. By increasing the number of Cu and PPG sheets, more horizontal array capacitors can be fabricated. Figure 4(b) shows a plane view of the synthesized epoxy impregnated with glass fiber, which acts as a dielectric between the electrodes. The microstructure of a fabricated horizontal array capacitor sample was characterized by scanning electron microscopy (JSM-6360, Jeol). A single glass fiber with a diameter of $8 \mu\text{m}$, comprising several pieces, was fabricated into one object. It was tied in a matrix form. Subsequently, one PPG sheet can be prepared by coating epoxy, which has high mechanical strength and can maintain high reliability in the process. The dielectric constant is low, but the rate of change in the temperature is fairly stable.

3. Results

Figure 5 shows that the fabricated samples (S_1 , S_2 , S_3 , and S_4) were soldered on the Printed Circuit Board to measure the electrical properties. The electrode circuit on the PCB was designed such that the array capacitor with five electrodes and four dielectrics was connected by soldering. The fabricated array capacitors (S_1 , S_2 , S_3 , and S_4) have different lengths and widths. The electrical properties of the array capacitors with four dielectrics between five electrodes were

measured using an electrode pad at the A-E points for sample S_3 on PCB.

Figure 6 shows the electrical properties of capacitance/impedance/ESR according to temperature and frequency from the measurement point of the fabricated sample S_3 . As shown in Figure 6(a), C_1 (A-B), C_2 (B-C), C_3 (C-D), C_4 (D-E), C_5 (A-C), C_6 (A-D), and C_7 (A-E) according to DC bias (0–40 V) were measured using a LCR meter (E4980A, Keysight Frequency 1 MHz, Level 1 V) from each measurement point on the PCB. Because the capacitance value of C_5 (A-C), C_6 (A-D), and C_7 (A-E) is a series circuit according to equation (1), it is expected to reduce by half. The measured average capacitance value of C_1 , C_2 , C_3 , and C_4 , as shown in Figure 6(a), is 1.98 pF, and each tolerance based on the average value has a value within 1%. Using the measured average values of C_1 and C_2 , the calculated capacitance value of C_5 can be interpreted as 0.94 pF but the actual measured value is 0.98 pF, which is approximately 4% tolerance. The measured value of C_6 was 0.65 pF, which corresponded to the value calculated by the serial circuit formula of C_1 , C_2 , and C_3 , respectively. However, the measured value of C_7 was 0.38 pF, but the tolerance was 20% when compared to the calculated value. Essentially, the rate of change of capacitance according to the bias voltage is excellent within 1% in the case of C_5 and C_6 . The DC bias voltage of this experiment measured the characteristics of capacitance at 40 V. However, the BDV characteristics of the PPG sheet used as a dielectric material in this study can be satisfactory even above 200 V. Figure 6(b) shows the rate of change of capacitance with temperature at C_1 (A-B) point. The TCC (temperature-capacitance-characteristics) curves

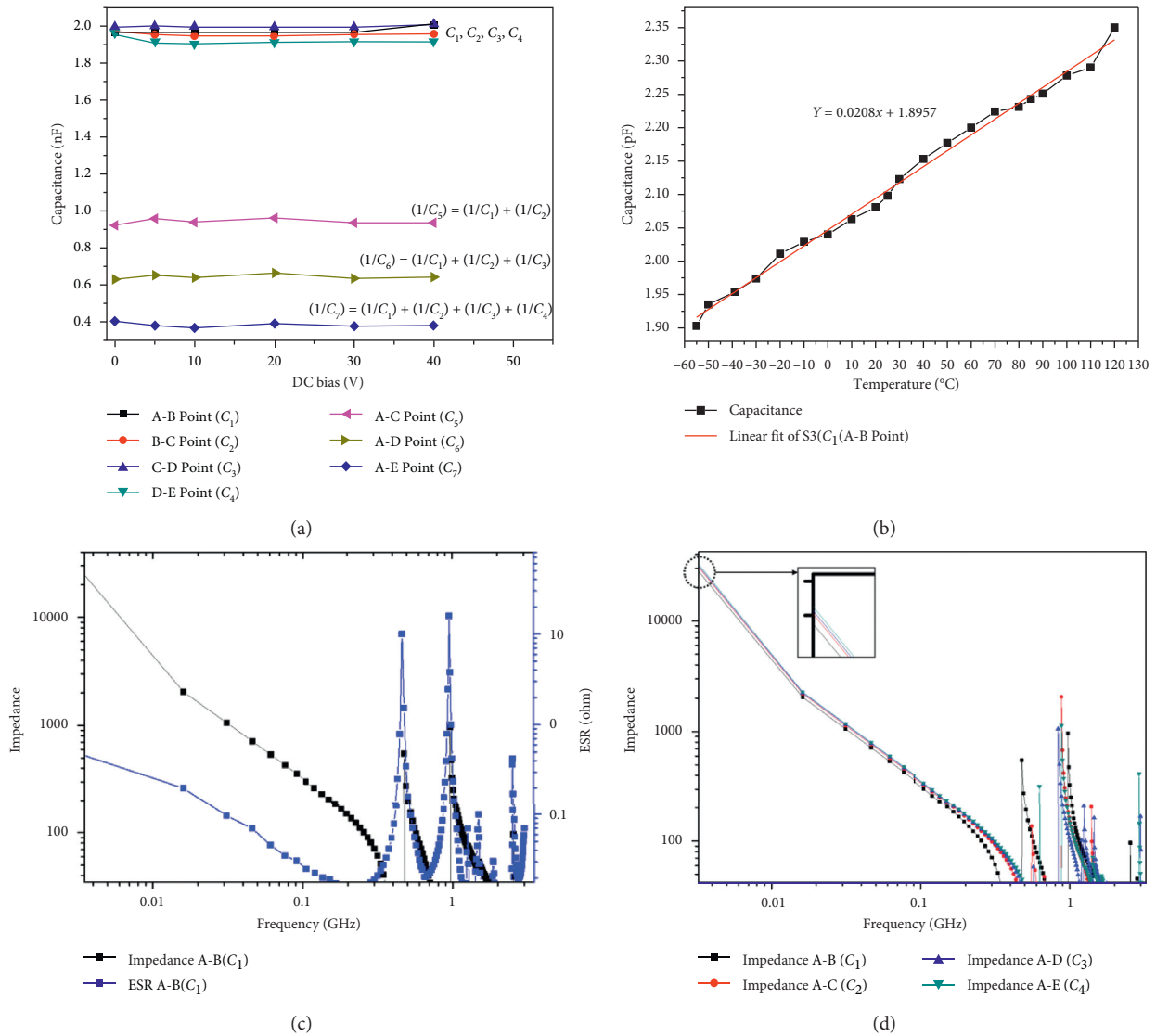


FIGURE 6: Electrical properties according to frequency. (a) Capacitance vs DC bias. (b) Capacitance vs temperature. (c) Impedance/ESR vs frequency @ C_1 . (d) Impedance vs frequency @ C_1, C_2, C_3, C_4 .

and capacitances were determined using a HP 4284A precision LCR meter (HP, USA) at a test voltage of 1 V and a frequency of 1 kHz. The range of temperature was measured from -55 to 120°C . At -55 , 25 , and 120°C , the capacitance was 1.903 , 2.098 , and 2.35 pF, respectively. As shown in Figure 6(b), capacitance measurements were taken in the temperature range from -55 to 120°C placing the array capacitors in a temperature chamber (S&A Inc., USA). The rate of change of capacitance maintains a nearly linear characteristic but it tends to increase finely from 120°C or more. The linear rate of change of capacitance according to temperature can also be used as a temperature sensor. The glass fiber impregnated in the epoxy has a low dielectric property but excellent temperature characteristics. It can serve as a sensor with an average of four temperature change distributions in one body. Here, the four capacitance change rates are C_1 (A-B), C_2 (B-C), C_3 (C-D), and C_4 (D-E). Each capacitance measured by temperature can more accurately

analyze the temperature distribution in the measurement environment. Figures 6(c) and 6(d) demonstrate the impedance and ESR versus frequency using an RF impedance analyzer (E4991A, keysight, 1 MHz~3 GHz) for C_1 . It can be seen that the waveform of impedance and ESR have the same periodic characteristics versus frequency. The resonance frequency was measured at 0.38 GHz. Several peak points of the reflected impedance after the resonance frequency are the waveform reflected from each electrode. The ESR was measured to be 11 ohm or less, and it was confirmed to increase at the position where the resonance frequency increased. If the characteristic values of the capacitors from C_1 to C_4 are known, similar electrical characteristics can be expected in the other capacitors (C_5 – C_9). Figure 6(d) shows the impedance measurements from C_1 to C_4 . It is evident that the impedance value increases from C_1 to C_4 because each measuring point has a different distance. Additionally, a higher frequency indicates greater fluctuations in the

impedance value, which is expected to be resolved by forming a PCB circuit suitable for high-frequency measurements. Further research is required to fabricate array capacitors of very small size and good high-frequency characteristics.

4. Conclusions

In this study, we propose unique array capacitors with a series-type structure in the horizontal direction using PPG sheets. Dielectric layer uses the PPG sheet materials of the impregnated glass fiber. The proposed array capacitors consist of 9ea capacitance using five Cu and four PPG sheets. We created useful and unique array capacitors using simple and unique manufacturing processes. The purpose of this study is to confirm that it can be applied to capacitor arrays based on the results obtained through basic theories and experiments. Additionally, the linear rate of change of capacitance according to temperature can be used as a temperature sensor. The electrical properties of the temperature sensor require further examination and analysis and are still under study. The results of the electrical properties can be applied to electronic circuits to demonstrate the possibility of reducing the size and noise of the module. The new manufacturing process described above is suitable for simple, cost-effective characteristics of organic materials when optimizing for the sophisticated cutting technology. In future, our research direction is to design a small-sized thin-array capacitor using high-capacity organic sheets as a composite dielectric layer of the impregnated glass-fiber epoxy material with reliability.

Data Availability

The authors declare that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Education (NRF-2016R1A6A3A11931569). This study was supported by the GRRRC program of Gyeonggi Province (GRRRC Sungkyunkwan 2017-B02: Development of MEMS-based ultra-thin & ultra-thin temperature/humidity/pressure convergence environment sensor), funded by the Material & Process Platform for Convergence Sensors.

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