

Research Article

High-Frequency Properties of Embedded Passives and Thermal Resistance in Organic Substrates for RF Module

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Radio Frequency (RF) modules have been miniaturized to meet the demand for smaller and more enhanced handsets for wireless applications such as cellular phones. However, area for passive devices used in RF modules has made further miniaturization difficult. Passives embedded in substrates are now being studied intensively. In addition, circuit simulation technology has been developed that enables efficient designing of RF module circuits. Circuit designers, however, have limited database of organic substrates and embedded passives. Further, optimized thermal designs are required to prevent thermal resistance increase due to miniaturization of substrates. In this paper, we describe the high-frequency properties of the capacitors embedded in the organic substrates and present the equivalent circuit models of the embedded capacitors. We also present the thermal design of organic substrates applicable to RF modules.

1. Introduction

Radio Frequency (RF) modules have been miniaturized to meet the demand for smaller and more enhanced handsets for wireless applications such as cellular phones. Smaller semiconductor devices and passives have been usually used for the miniaturization of modules, but it is sometimes required to embed passives into substrates for further miniaturization. Embedded passives have been studied with ceramic substrates such as LTCC (Low Temperature Co-fired Ceramic) or silicon substrates to date, and studies with organic substrates are becoming active recently because of the advantages of CTE (Coefficient of Thermal Expansion) matching to motherboards and the manufacturing cost [1–12]. For designing circuits, the simulation is becoming more important to improve the efficiency of R&D. However, the information on the electrical properties and the circuit design of organic substrates are so poor that the efficient usage of organic substrates is difficult for designers.

In this paper, we describe high-frequency properties of capacitors embedded in organic substrates and present

equivalent circuit model of embedded capacitors. We also present the thermal design of organic substrates applicable to RF modules.

2. Embedded Passives in an Organic Substrate

2.1. The Concept of Embedded Passives. Figure 1 is a conceptual model of embedded passives with an organic substrate for RF module. It embeds a thick film capacitor, a thin film capacitor, and an inductor. The thick film capacitor is formed by assembling high-dielectric-constant material between electrodes and the thin film capacitor is formed with high-dielectric-constant film as well. The inductor is formed by patterning. We describe the properties of the embedded thick film capacitors.

2.2. Cross-Section of the Embedded Capacitor. Figure 2 is the cross-sectional photograph of the test substrate with the embedded capacitor. The base material of the test substrate was MCL-E-679 which is manufactured by Hitachi Chemical Co., Ltd. The high-dielectric-constant material was

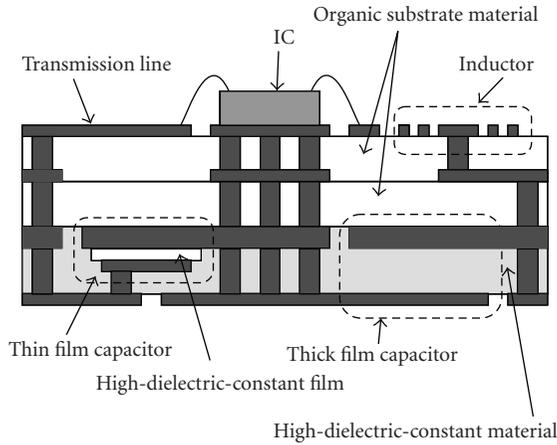


FIGURE 1: A conceptual model of embedded passives.

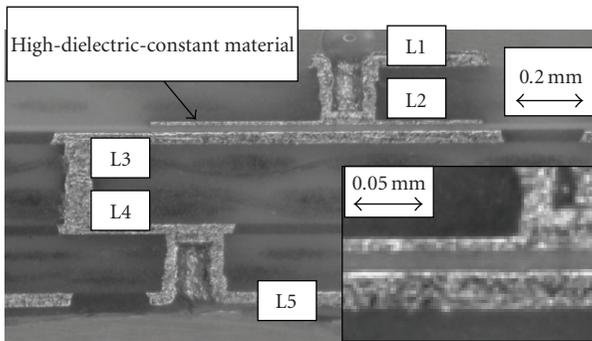


FIGURE 2: The cross-sectional photograph of the embedded capacitor.

composite material of epoxy resin, barium titanate filler, and so on. The dielectric constant was 45 (1 MHz). The circuit was fabricated between Layer 1 and Layer 5 through the via-holes and the capacitor was formed between Layer 2 and Layer 3. Layer 2 and Layer 3 form the electrodes and the pattern area is equal to the electrode area. The thickness of the layer of the high-dielectric-constant resin between Layer 2 and Layer 3 was 20 micrometer. The test patterns for the single capacitor property and the single outer layer via-hole property were also formed in addition to the circuit test patterns.

2.3. The High-Frequency Properties of the Embedded Capacitors and the Equivalent Model Simulation Analysis. We used VNA 8510C (Agilent) as the measurement equipment and ACP40 GS650 (Cascade) as the high-frequency probe for the measurement of the high-frequency circuit properties. The circuit properties were obtained by contacting the high-frequency probe to the pad of Layer 1 and executing one-port measurement for S-parameter. The edge of Layer 5 was shortened to the ground pattern with solder. Figure 3 shows the equivalent circuit models of a via-hole TEG (Test Element Group) and a capacitor TEG modeled with the high-

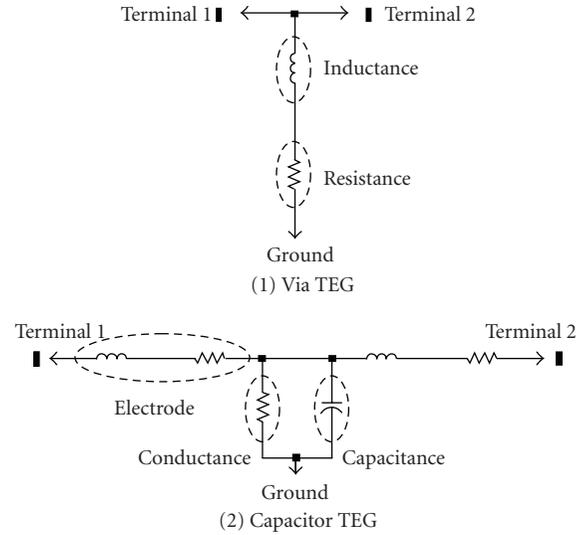


FIGURE 3: The equivalent circuit models of a via-hole TEG and a capacitor TEG.

frequency circuit simulator (Agilent ADS: Advanced Design System). The via-hole TEG is modeled by using inductance and resistance in series. The capacitor TEG is modeled by using inductance and resistance in series and capacitance and conductance in parallel. Figure 4 is the high-frequency properties of capacitance and Q value calculated using the measured S-parameter of the capacitor TEG. Although the capacitance depends on frequency due to the influence of parasitic inductance, the fabricated capacitor is practically usable up to 6 GHz. Q value was calculated using the following equation: $Q = 2 * \pi * f * C/G$ (f : frequency, G : conductance). The large Q value indicates that the capacitor is a superior one with low loss. The maximum Q value of the fabricated capacitor was around 25 in Figure 4.

The relationship between electrode area and capacitance can be obtained by the equivalent circuit model analysis. Figure 5 is the analyzed result of the capacitor test patterns with the different electrode areas. It was confirmed that the capacitance was proportional to the electrode area as was theoretically expected.

Figure 6 shows the equivalent circuit model of the test pattern having an embedded capacitor and Figure 7 is the result of the measurement and the simulation in Smith chart. The trace swept on lower semicircle and showed the capacitor characteristics because the circuit property was subject to a capacitor in low frequency. The frequency of the resonant point of this circuit where the trace moves from lower side to upper side was 1.69 GHz. The property above the resonant frequency was subject to inductors of via-holes and others. The trace swept and showed the inductor characteristics. As shown in the figure, the simulated data of the embedded capacitor agreed with the measured one. The result mentioned above indicates that the circuit properties can be simulated and estimated by modeling via-holes and capacitors.

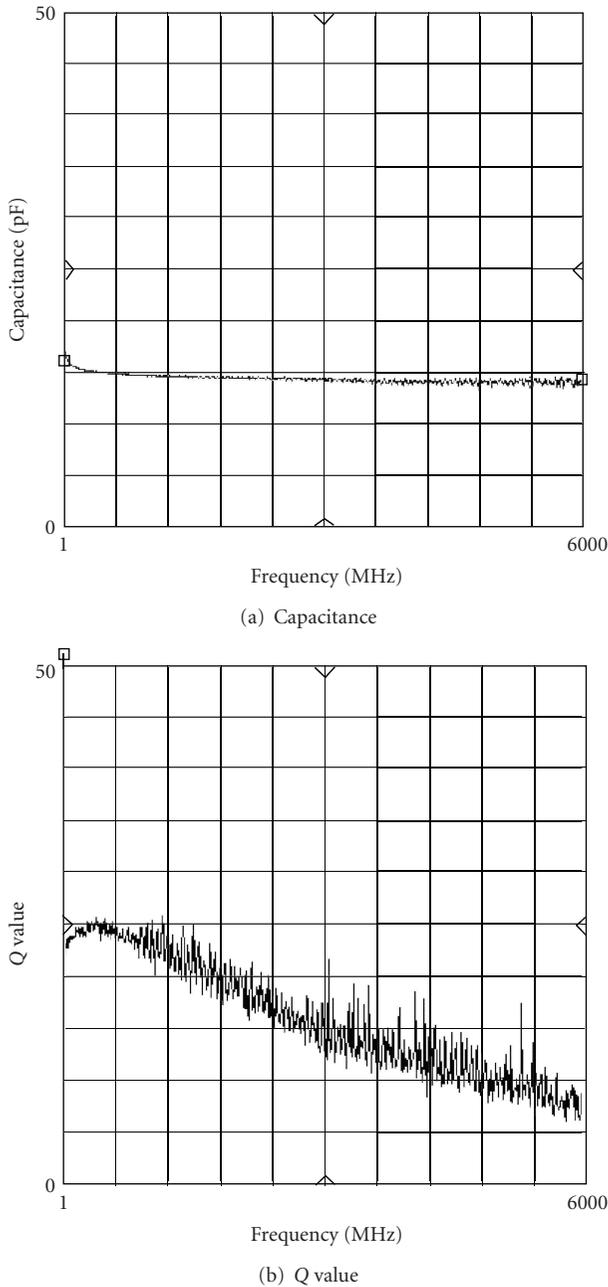


FIGURE 4: The high-frequency properties of the capacitor TEG.

3. Thermal Resistance in Organic Substrates

We studied six types of substrates with various chip mounting, via-hole, and through-hole layout. The structures are shown in Figure 8. The substrate sizes were 4×4 – 6×6 mm and the layer count of core plus buildup layers was 6. (*Type A*. An IC chip was mounted on the top layer which was connected to the bottom layer through the via-holes. *Type B*. An IC chip was mounted on the top layer and the through-holes were fabricated on the edge of the substrate. *Type C*. An IC chip was mounted in the cavity which was fabricated between Layer 1 and Layer 3 and the through-holes were

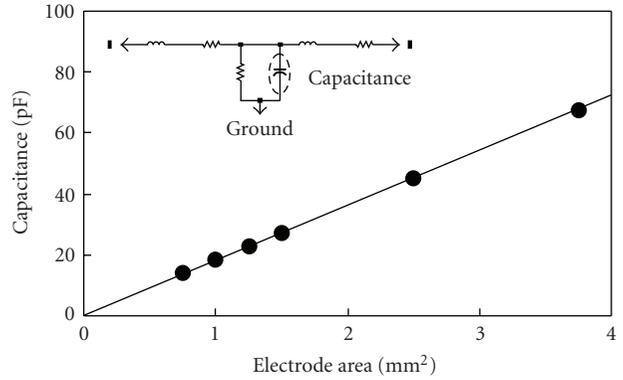


FIGURE 5: The relationship between electrode area and capacitance.

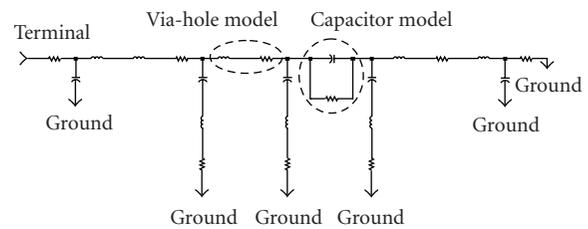


FIGURE 6: The equivalent circuit model of the test pattern having an embedded capacitor.

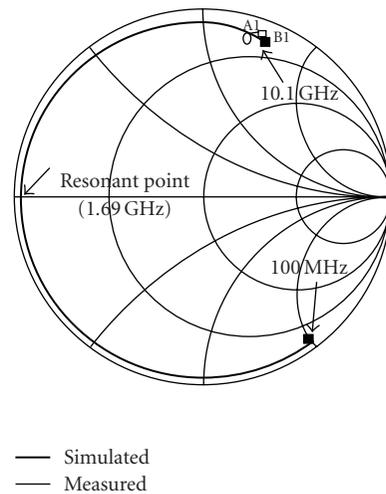


FIGURE 7: The high-frequency properties of the embedded capacitor.

fabricated on the edge of the substrate. *Type D*. The cavity was fabricated from the bottom layer and an IC chip was mounted in the cavity. The through-holes were fabricated on the edge of the substrate. *Type E*. An IC chip was mounted on the bottom layer. This structure had no thermal via-holes. Heat spreads through the bottom layer and the solder balls. *Type F*. An IC chip was mounted on the top layer and the through-holes were fabricated from the top layer to the bottom layer.) The thermal resistance was calculated using the measured DC current gain and the power consumption by the IC chip. The result of the assessment showed that the

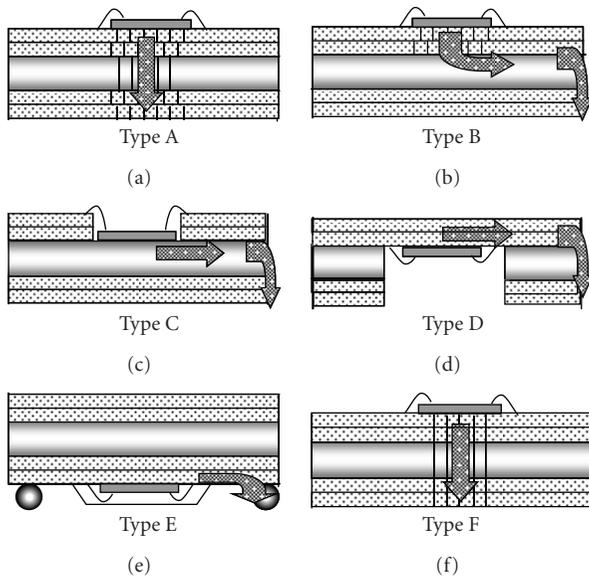


FIGURE 8: The substrate structures with various chip mounting, via-hole, and through-hole layout.

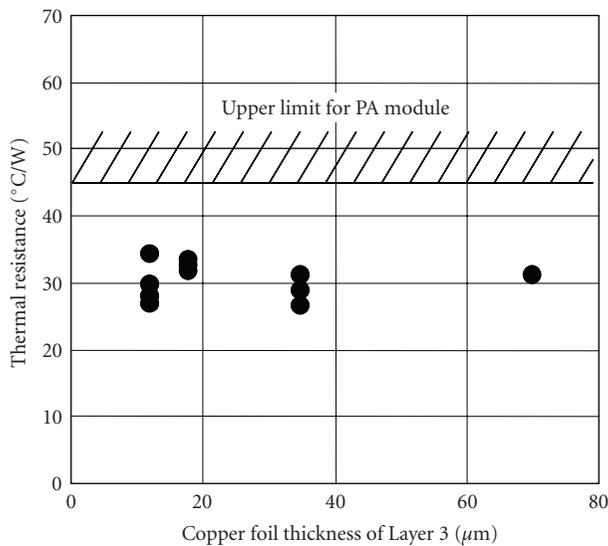


FIGURE 9: The relationship between the thickness of copper foil of Layer 3 and the thermal resistance.

substrates of type B, C, and D have superior heat dissipation properties and the heat of IC chip spreads effectively via the through-holes on the edge of the substrates. It is interesting that the simplest structure, type B, showed the excellent thermal property. Figure 9 shows the relationship between the thickness of copper foil of Layer 3 and the thermal resistance in type B. As shown in the figure, the thermal resistance of type B was fairly less than the upper limit for PA module, 45°C/W , regardless of the thickness of copper foil. Figure 10 shows the dependence of the thermal resistance on the thickness of the copper area rate. It is obvious that the requirement of the thermal resistance is satisfied when the rate is higher than 40%. Thus the organic substrate can be

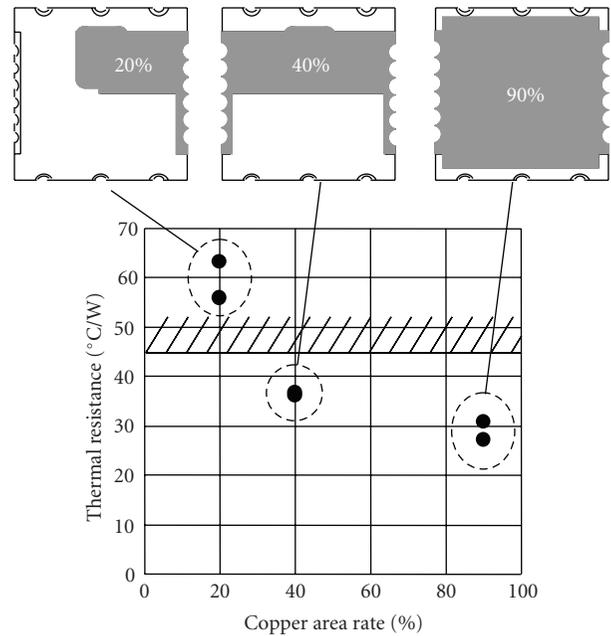


FIGURE 10: The dependence of the thermal resistance on the thickness of the copper area rate.

utilized for the miniaturized RF module by applying a new structure which decreases the thermal resistance.

4. Conclusions

The high-frequency properties of the embedded capacitors were measured. The resonant frequency and Q value are dropped by the parasitic components of the device. The method to analyze the equivalent circuit models was found to be useful to make clear the parasitic component values and the properties of the module. The organic substrate which has a new structure to decrease the thermal resistance was found to be applicable to the miniaturized PA module.

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