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基于环氧树脂 / 钛酸钡 / 聚酰亚胺绝缘介质的 PCB 埋嵌电容的制作及性能研究

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摘　要　文中使用叠层技术制作了以环氧树脂 / 钛酸钡 / 聚酰亚胺为绝缘介质的 PCB 埋嵌电容器。制作的电容器容值与设计值之间误差在 － 4.0% 到 － 6.0% 之间。通过将电容器面积增加 5%，电容器容值误差降低到了 － 1.1% 以下。为了检测埋嵌电容器的可靠性，分别进行了 260℃ 回流焊、高低温冷热冲击、85℃ /85% RH 及高压击穿测试。测试结果表明，以环氧树脂 / 钛酸钡 / 聚酰亚胺为绝缘介质的 PCB 埋嵌电容器有良好的环境可靠性，适合用于制作 PCB 埋嵌电容器。

关键词　钛酸钡；埋嵌电容；印制电路板；可靠性
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Fabrication and Characterization of Embedded Capacitors in PCB Using Epoxy/$BaTiO_3$/PI Capacitor CCL

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Abstract　The embedded capacitors in PCB (Printed Circuit Board) were fabricated using commercial epoxy/BaTiO3/PI capacitor CCL in conventional PCB build-up process. Capacitance measuring demonstrated the tolerances of the obtained capacitors ranged from −4.0% to −6.0%, and special design to compensate the capacitor geometry significantly decreased the tolerance to −1.1%. Reflow process at 260℃, high thermal cycling, 85℃/85% RH and high-voltage breakdown tests were performed to evaluate the reliability of embedded capacitors. It is summarized that the fabrication of epoxy/$BaTiO_3$/PI composite embedded capacitors is successfully demonstrated using conventional PCB build-up processes, and their environmental reliability are evaluated to be excellent.

Keywords　$BaTiO_3$; embedded capacitor; reliability; printed circuit board

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1 Introduction

Due to steadily increasing operating frequencies and the lowering of supply voltage in digital systems, simultaneous switching noise (SSN) is a serious concern, because it can affect the performance of high-speed systems[1,2]. Embedding capacitors in the inner layers of a circuit board is the preferred method to effectively decrease the SSN without increasing the size of product[3,4]. Accordingly, this method is of great interest to printed circuit board (PCB) manufacturers, especially to those who produce portable products with a wide range of operating frequencies[5-7].

The development of embedded capacitors should be divided into three parts: material, manufacturing process, and embedding reliability[7]. A polymer/ceramic composite is one of the promising materials to fabricate embedded capacitors[8,9]. The epoxy/$BaTiO_3$ is the preferred choice, because it has the combining advantages of dielectric constant of ceramic powders, good compatibility with PCBs, and excellent process ability of polymers[9]. Several approaches were employed toward the realization of embedded capacitor technology. The important techniques include sputtering, sol–gel, hydrothermal synthesis, anodization, screen printing, spin coating and roll coating[1]. For the mass-production, it is subjected to the build-up process using the copper clad laminate (CCL). The CCL contains the capacitor material deposited between the copper layers by the above-mentioned technologies[10]. The reliability of the embedded capacitors ultimately determines the breadth and success of their practical applications. The capacitance of an embedded capacitor can change due to various environmental stresses. The effect of various environment, such as thermal aging, temperature cycling, and temperature-humidity on the epoxy/$BaTiO_3$ were investigated by many capacitor reliability tests[1,11,12].

3M C-ply product performance test showed that the breakdown voltage of epoxy/$BaTiO_3$ substrate was around 1500 V with the thickness of 1/2 mil[13]. Capacitors with epoxy/$BaTiO_3$ dielectric experienced less than 10% decrease in capacitance after 1400 cycles at −55℃ and 125℃[11]. Lee et al.[14] fabricated the embedded capacitors aged at 85℃/85% RH for 24 h and reflowed three times at 260℃ for 60 s, respectively. The results showed that the capacitances were increased by 10% due to moisture absorption and decreased by 30% after solder reflow process. Polyimide (PI) has excellent thermal reliability with Tg up to 260℃ and low water absorption less than 1%[15]. The PI introducing in the epoxy/$BaTiO_3$ should improve the capacitive reliability of the as-embedded capacitor for PCB.

In this study, we have produced embedded capacitors in PCBs using multilayer PCB build-up process. A commercial epoxy/$BaTiO_3$/PI embedded capacitor CCL was employed as the substrate. The reliability of as-fabricated capacitor was evaluated by various environmental tests, including thermal shock, high-voltage breakdown, thermal cycling and 85℃/85 % RH tests.

2 Experimental

2.1 Materials

The used embedded capacitor CCLs were purchased from Mitsu Co. Ltd. (MC25L and BC12TM). The capacitive properties of CCL, including the dielectric constant (ε_r), the D_f and capacitance value, were listed in table 1. Note that the listed parameters in

Table 1. The properties of capacitor CCL BC12TM and MC25L

Capacitor CCL	Insulation layer thickness/μm	Composition of insulating layer	Capacitance value/ ($pF \cdot cm^{-2}$)	ε_r	D_f	CTE/ ($ppm \cdot ℃^{-1}$)
BC12TM	12	epoxy/$BaTiO_3$/PI	650	4.4	0.015	23
MC25L	24	epoxy/$BaTiO_3$/PI	130	3.9	0.004	30

table 1 were tested at the frequency of 1 MHz.

2.2 Design and Fabrication

The fabricated capacitors were embedded in the 10-layer PCB by CCL BC12TM and 4-layer PCB by CCL MC25L. Their geometries were designed into the rectangle structures with the size of 8.73 mm×24.575 mm and circle structures with the diameter of 10.21 mm, respectively. These two capacitor structures were embedded in the 4^{th} and 5^{th} layers, 6^{th} and 7^{th} layers for the 10-layer PCB, and the 2^{nd} and 3^{rd} layers for the 4-layer PCB. The PCBs were assembled by the conventional build-up process. The build-up structures were shown in Fig. 1.

2.3 Characterizations

The capacitance values were measured by the LCR of HIOKI 3532-50 at the frequency of 1 MHz. Yangzi YD 9810 was employed to define the breakdown voltage of the capacitor insulating layer. Note that the voltage was increased from 0 V at the rate of 100 V/min. The reliability of embedded capacitors was investigated by thermal cycle during two temperatures, −55℃ to 125℃. The morphologies of embedded capacitors were characterized by Olympus optical microscope.

3 Results and Discussion

Prototype scale embedded capacitors in organic substrates were fabricated using conventional PCB build-up process. Fig. 2 illustrated the fabricated

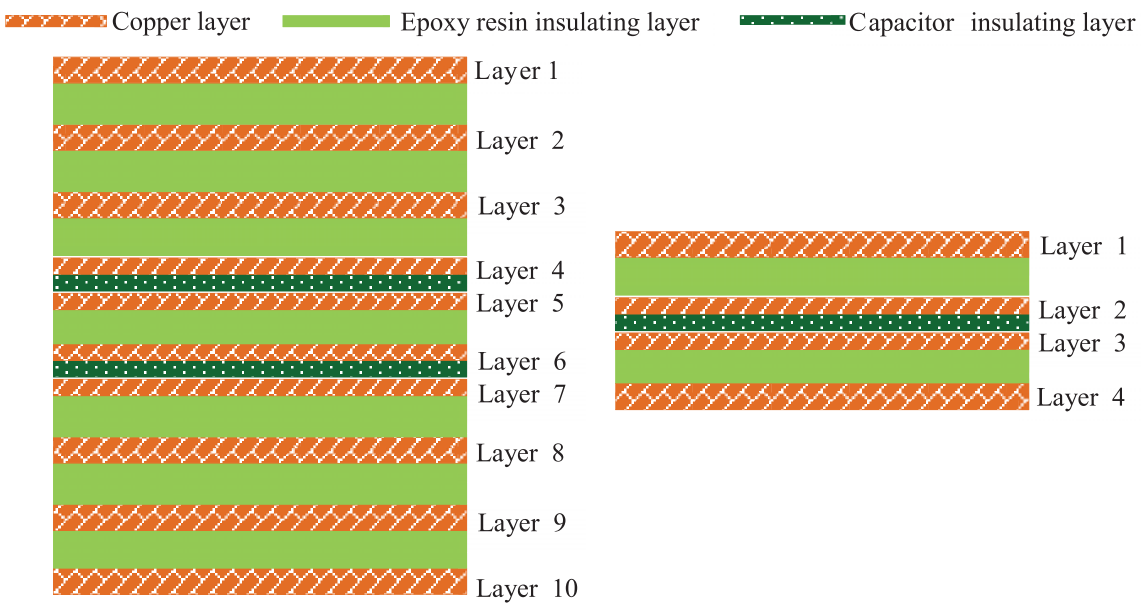
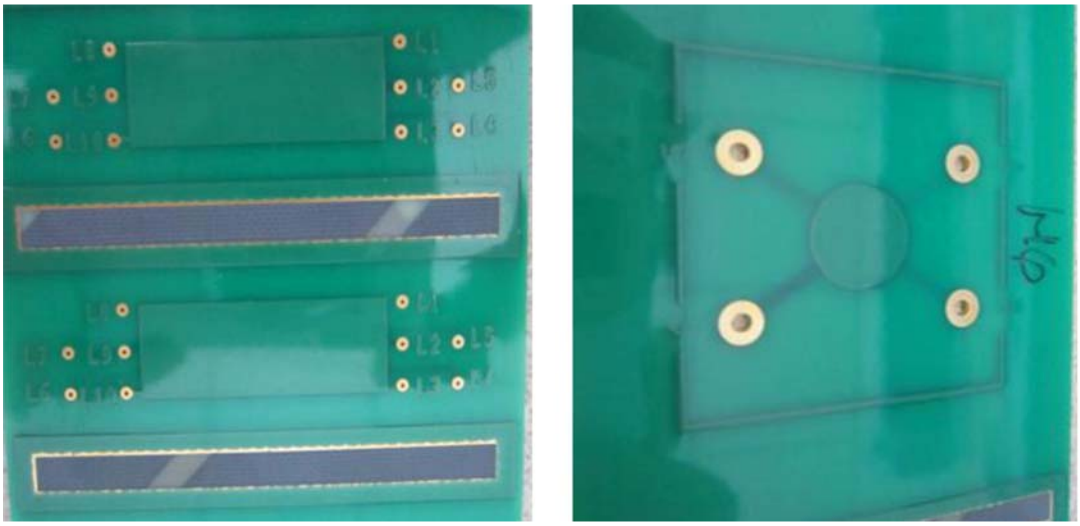


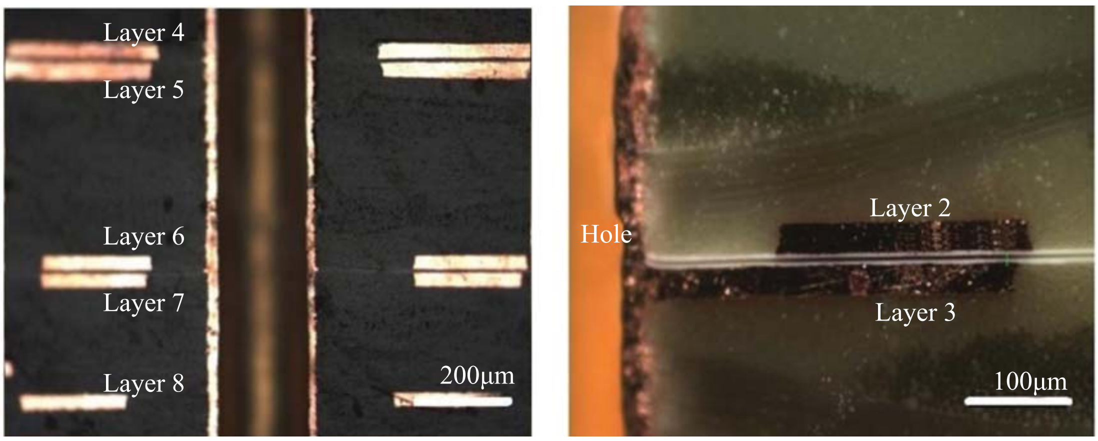
Fig. 1. Build-up structures of the multilayer PCB used to embedded capacitors

capacitor samples. The 10-layer PCB with embedded rectangle capacitor was showed in Fig. 2(a), and the Fig. 2(b) displayed the circle capacitor embedded in the 4-layer PCB. The as-plated holes were used as the points for capacitance testing. The cross-section images of the rectangle capacitor in 10-layer PCB were shown in Fig. 2(c) and 2(d). It can be seen that the capacitor consists of two-flat coppers as the electrodes and the very thin sandwiched materials as the dielectric layer. The capacitances of these embedded capacitors with different geometries and different CCL materials were detailed as shown in table 2.

Table 2 demonstrated the effects of embedded position and capacitor geometry on the capacitance tolerances. As seen from the data, the embedded position and geometry do not make obvious effects on the capacitance. All the capacitors were calculated in the range of −4.0% to −6.0% in capacitance tolerance. The tolerance of an electronic component is the quantitative magnitude for evaluating the value variation to meet practical needs. For the sake of uniformity, capacitors ranked with 5% (first grade), 10% (second grade) and 20% (third grade)



(a) rectangle capacitor embedded in 10-layer PCB　(b) circle capacitor embedded in 4-layer PCB



(c) and (d) cross-section of rectangle capacitor embedded in 10-layer PCB

Fig. 2.　The images of fabricated capacitor samples

tolerance to standard values, are generally accepted by electronic manufacturers[16,17]. Obviously, the as-fabricated capacitors belong to the first grade or the second grade components.

As was shown in the table 2, the capacitance variances are lower than 5%, indicating these fabricated capacitors significantly concentrate on the average capacitances. We tried to decrease the capacitance tolerances by the geometry compensation. The copper panel area of the embedded capacitor was increased by 5%. Accordingly, the rectangle structure embedded in L4/L5 was revised to 9.00 mm×25.00 mm. Table 3 listed the capacitances of the compensated capacitors embedded in L4/L5. It showed that the capacitance tolerance was greatly decreased from −6.0% to −1.1%

Table 2. The capacitances of these embedded capacitors with different geometries and different CCL materials

Embedded position	Designed capacitance/ pF	Capacitances at 1 MHz/ pF			Average capacitance/ pF	Capacitance tolerance	Capacitance variance
L4/L5 with rectangle structure (8.73 mm×24.575 mm)	1395	1313.0 1315.0 1312.6 1312.8	1311.5 1320.1 1310.4 1314.1	1309.0 1309.2 1308.3 1316.7	1312.7	−6.0%	0.25%
L4/L5 with circle structure (Φ10.21 mm)	530	498.1 501.3 499.0 497.7	494.9 502.3 504.9 498.3	494.4 500.4 497.1 497.8	498.6	−5.9%	0.57%
L4/L5 with rectangle structure (8.73 mm×24.575 mm)	1395	1309.6 1319.2 1306.8 1312.6	1305.2 1310.1 1302.8 1306.1	1306.7 1303.4 1310.3 1313.5	1308.9	−6.2%	0.34%
L4/L5 with circle structure (Φ10.21 mm)	530	494.2 499.7 494.9 498.8	499.9 504.9 500.4 490.2	502.5 498.3 505.1 499.4	499.0	−5.8%	0.83%
L2/L3 with rectangle structure (8.73 mm×24.575 mm)	279	265.7 269.2 260.5 262.8	271.2 264.5 266.8 271.3	269.8 259.5 267.4 260.7	265.8	−4.73%	1.52%
L2/L3 with circle structure (Φ10.21 mm)	106	98.1 100.3 99.1 101.8	99.4 102.0 101.2 97.2	103.6 103.4 98.3 103.6	100.7	−5.0%	2.1%

Table 3.　The capacitances of the compensated capacitors

Embedded position	Designed capacitance/pF	Capacitances at 1 MHz/pF			Average Capacitance/pF	Capacitance tolerance
L4/L5 with rectangle structure (9.00 mm×25.00 mm)	1395	1378.6 1395.2 1390.0 1378.4	1383.6 1371.5 1378.5 1375.8	1374.4 1387.7 1373.7 1370.6	1379.9	−1.1%

Table 4.　The breakdown voltages of the embedded capacitors

Capacitor No.	1	2	3	4	5	6	7	8
Breakdown voltage/V in 10-layer PCB	2430	2390	2420	2400	2400	2390	2410	2450
Breakdown voltage/V in 4-layer PCB	2780	2760	2770	2780	2690	2780	2750	2750

by geometry compensation, implying that these as-fabricated capacitors were upgraded from the second grade to the first grade.

The failure as a result of an abrupt drop in insulating resistance during voltage increasing was proposed to verify the insulation of the dielectric layer. Table 4 listed the breakdown voltages of the embedded capacitors in the 10-layer and 4-layer PCB, respectively. The voltage was elevated at a rate of 100 V/min. The data showed that the capacitors can withstand the voltage higher than 2000 V, which can significantly satisfy the requirements of 500 V or higher in the electronic circuit module.

Because embedded capacitors in PCB would undergo solder reflow process, the stability of electrical properties at solder reflow condition should be confirmed. The thermal shock stability of embedded capacitors was reflowed in the production line for 6 times (about 15 min for each time). The reflowing temperature was set at 260℃. Fig. 3 plotted the capacitances of the embedded capacitor in relation to the thermal shock times. It can be seen that the capacitance has a little decreasing less than 1% at the 1^{st} or 2^{nd} round thermal shock. At the further thermal shock, the capacitor was gradually kept a constant value. This verification demonstrates that the capacitors have very good thermal shock reliability.

Temperature cycling tests are expected to induce deformation, delamination or stress relaxation in the embedded capacitor, leading to an effect on the capacitance. Generally, the residual-stress relaxation took place during the initial 100 to 300 cycles. Therefore, thermal cycling test at −55℃/15 min and 125℃/15 min for 300 cycles was performed to illustrate the capacitance variances. Fig. 4 showed the results. As was indicated in Fig. 4, the thermal cycling made a very limited effect on the capacitance of the embedded capacitors. For the rectangle structure of 1395 pF, the 300-cycle processing decreased the capacitance less than 5%. The circle structure decreased about 4% in capacitance. The stress-relaxation for capacitor embedding did not result in obvious variance of capacitance, indicating these

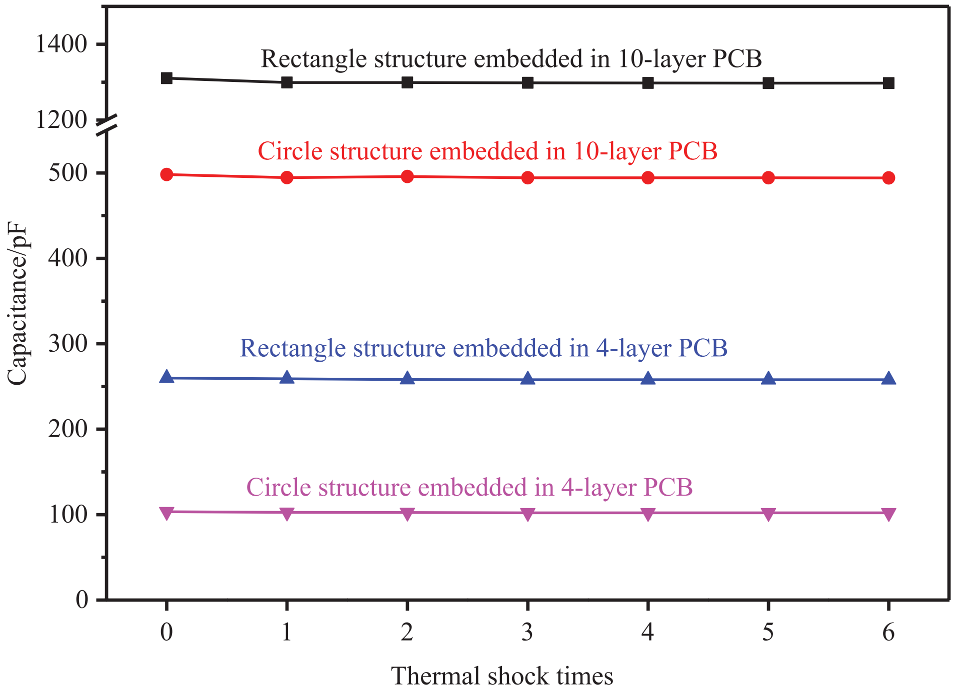


Fig. 3. The capacitances of the embedded capacitor in relation to the reflow times

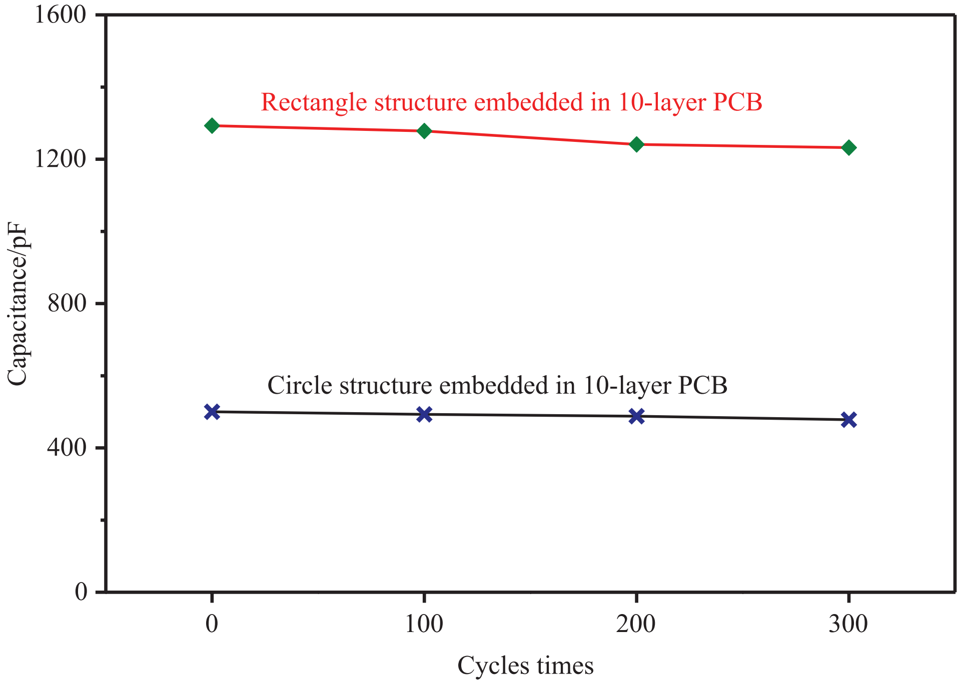


Fig. 4. The capacitance of the embedded capacitor in relation to the thermal test cycles

fabricated capacitors showed very excellent thermal cycling reliability to eliminate the inner stress.

Under humidity conditions, the dielectric constant of epoxy/$BaTiO_3$/PI composite increases due to water absorption. It can be understood that absorbed moisture changes molecular dipoles. Polar group of water increases polarity of composite, and it results in increase of capacitance[18,19]. Fig. 5 showed the changes of capacitance during 85℃/85% RH test for 336 h. We can see that the capacitances increased less than 5% compared to initial capacitance, indicating the moisture absorption did not obviously lead to the delamination and cracks in the dielectric.

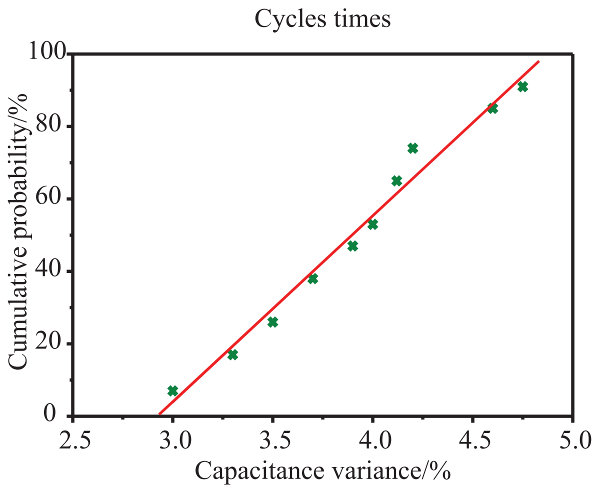


Fig. 5. The capacitance variances after 85℃/85% RH test for 336 h

4 Conclusion

The embedded capacitors in PCB were successfully fabricated using commercial epoxy/$BaTiO_3$/PI capacitor CCL in PCB mass-production line. The average capacitances of the obtained capacitors were deviated from the designed values in the range of −4.0% to −6.0%. With the geometry compensation, the tolerance of the revised capacitor was decreased from −6.0% to −1.1%. To evaluate the reliability of embedded capacitors fabricated by epoxy/$BaTiO_3$/PI composite, reflow process at 260℃, high thermal cycling, 85℃/85% RH, and high-voltage breakdown tests, were performed. There was no obvious electrical failure for embedded capacitors in the reliability tests. The capacitance changes of epoxy/$BaTiO_3$/PI due to the thermal and moisture effects are very small generally lower than 5%. Accordingly, the addition of PI in epoxy/$BaTiO_3$ showed a better environmental stability for this embedded capacitor in comparison to that of the pure epoxy/$BaTiO_3$ dielectric.

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