Development of Novel Thin Material for Decoupling Capacitors Embedded in PWBs

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Abstract
Many techniques have been developed to embed capacitors in printed wiring boards (PWBs) these days. The simplest way may be embedding chip capacitors in PWBs. However, since their thickness is over 200 m, the PWBs must be much thicker. In addition, prepregs or semi-cured insulators for lamination should be prepared with cavities for embedding them. Polymer composite materials with high-permittivity ceramic filler are a second candidate for embedding capacitors. However this technique needs large area to make decoupling capacitors because of their low capacitance. The best solution should be embedding thin film capacitors having large capacitance.

Now we have developed a novel dielectric insulator and thin film capacitors with the insulator. The capacitor has the structure of metal / insulator / metal (MIM). Both the metal electrodes are copper, and the thin insulator has a high permittivity for large capacitance. The total thickness, including the electrodes and the thin insulator, is less than 50 m; therefore, we need not use prepregs with cavities for capacitor embedding, and the PWB can be kept thin.

We also evaluated the electric properties of the thin film capacitor. The capacitance density was 1 nF/mm^2 at 1 MHz. The resonant frequency was higher than that of the chip capacitor with the same capacitance. The leakage current was about 1 nA/mm^2 at 4 V. We also proposed the process for embedding the thin film capacitors in PWBs.

Introduction
Signal integrity has become one of the most important problems nowadays, because cellular phones and portable electronic appliances have been improving for higher performance and downsizing with multi functions. Use of decoupling capacitors with 1-100 nF capacitance is an effective means of stabilizing the voltage of ICs. Stability of the voltage is needed to realize good signal integrity. The problem for higher performance is to reduce the equivalent series inductance (ESL). Lower ESL is needed in GHz-signal applications to shift the resonant frequency to higher. The problem with miniaturization is how to keep the area for the decoupling capacitors on PWBs. Therefore, capacitor embedding techniques have been focused in these applications.

In the last decade, many techniques have been developed for embedding capacitors in PWBs. Varieties of polymer composite materials with high-permittivity ceramic fillers have been reported as thick film capacitors [1, 2]. Their advantages are the matching of the coefficient of thermal expansion with those of the organic materials of PWBs, and the possibility of mass production with large size boards. The relative permittivity is 20-50, which is comparatively higher than the conventional PWB materials. Besides them, ceramic thick film fired at a high temperature such as 900^{o}C [3] and ceramic thin film such as lead lanthanum zirconium titanate (PLZT) [4] have been reported for use in embedding capacitors. Embedding of chip capacitors has also been reported [5].

Problems of decoupling capacitor embedding
Although many techniques mentioned above have been examined, the simplest way may be embedding chip capacitors in the boards, the chip capacitor meaning a chip monolithic ceramic capacitor in this paper. Certainly they have enough capacitance (1-100 nF) for decoupling capacitors. One of the problems of chip capacitors is their thickness: for example, 300 m for the 0603-size chip capacitor and 200 m for even the smallest 0402-size one. They are much thicker than one insulation layer of PWBs such as 100 m thick, so that PWBs with embedded chip capacitors must be much thicker than the ones without them. Figure 1 shows the cross section of a PWB with an embedded 0603-size chip capacitor. Obviously, the thickness of the layer where the chip capacitor is located is more than 300 m. Prepregs with cavities should be prepared for such chip capacitor embedding. The process of cutting prepreg cavities is the additional one to the conventional manufacturing process.

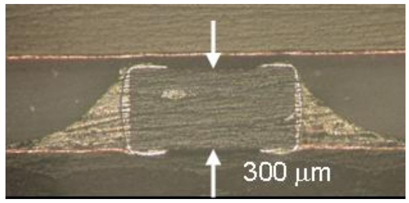

Figure 1 – Cross section of PWB with an embedded 0603-size chip capacitor

As for less thick capacitors, polymer composite materials with high-permittivity ceramic filler can be used for thick film capacitors which have 10-50 m thickness. However, these materials are limited to be thicker than 10 m because of their insulation necessity. Therefore, their capacitance is less than 20 pF/mm^2, which is too low for decoupling capacitors. As seen in Equation 1, the permittivity and the thickness of the insulator used will determine the capacitance. Thinner capacitors have an advantage for realizing larger capacitance. Therefore, the best solution should be embedding thinner capacitors with larger capacitance. We must consider further the process compatibility with PWB manufacturing besides the thickness of the capacitor.

$$C = \frac{\varepsilon \cdot A}{t}$$

C : Capacitance of capacitor
ε : Permittivity of insulator
t : Thickness of insulator
A : Area of electrode

Equation 1 – Capacitance calculation formula

MIM material for thin film capacitor

Our novel material for the thin capacitor is depicted in Figure 2. It has metal / insulator / metal (MIM) structure and the total thickness is less than 50 m. Both the upper and lower electrodes are made of copper, which is superior to other metals in conductivity and cost. Considering the handling processability, the thickness of the lower electrode is 35 m; that of the upper one is 10 m, because it must stop the laser beam in the laser drilling process to make via-holes between the upper electrode of the capacitor and the circuit trace in the PWBs. The insulator is a lead (Pb)-free material for environmental protection, and its thickness is less than 0.5 m for large capacitance of 1 nF/mm^2.

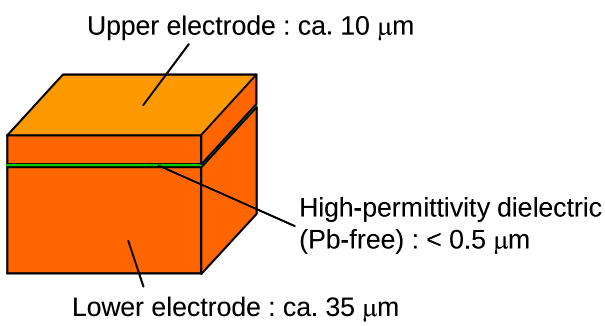

Figure 2 – Schematic view of MIM material structure

Discrete thin capacitor and its embedding process

Roughly classified, there are two methods to embed capacitors in PWBs by using our MIM material. The difference is the timing to manufacture the thin film capacitor. One is to laminate MIM material with the substrate board firstly and then to make electrodes 'in situ' on the board. Another is to make some pieces of thin film capacitors from MIM material firstly and then to attach the discrete thin capacitors on the substrate board with adhesives.

The latter has an advantage over the former because we can inspect the properties of the capacitors before embedding. Once a capacitor is embedded in the PWB, it is very difficult to repair or exchange it. Therefore, discrete capacitors inspected beforehand, which should be called 'known good components' (KGCs), will be used for getting excellent performance. We then manufactured discrete thin capacitors from the thin MIM material. The upper electrodes were patterned and etched to appropriate sizes designed from 1 mm^2 to 100 mm^2. The thin MIM materials with etched upper electrodes were then cut in pieces to be discrete thin capacitors. Figure 3 shows a prototype of the discrete thin capacitor for embedding; its upper electrode size was design to be 10 mm x 10 mm (100 mm^2). The left photograph of Figure 3 shows the top view of the capacitor; the right is a SEM image of its cross section. Three layers corresponding to MIM can be seen clearly.

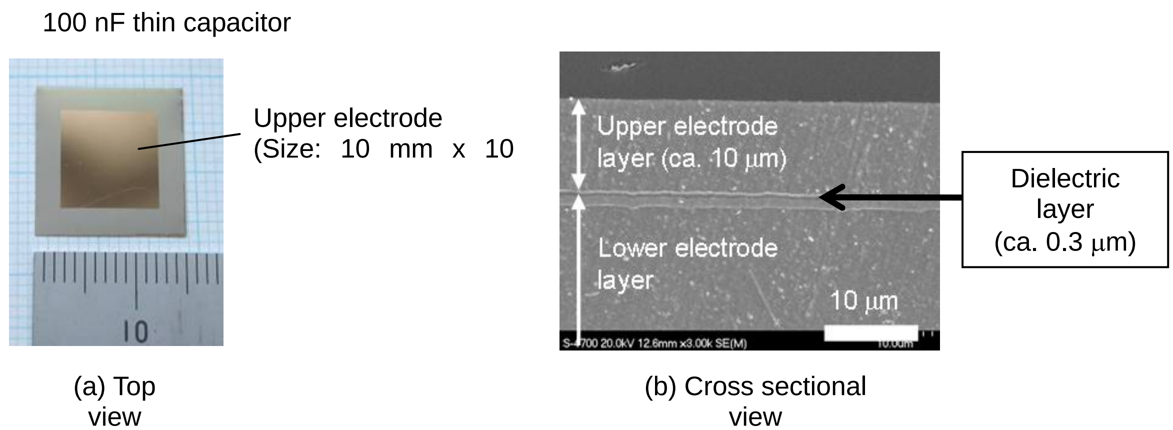

Figure 3 – Discrete thin capacitor

Figure 4 shows the recommendable processes for embedding a discrete thin capacitor in a PWB. The additional process is only mounting a capacitor on the surface of the inner board (No. 2 step). In the next process (No. 3 step), there is no need to use prepregs with appropriate cavities in lamination, because the capacitor is easy to be embedded without any bumps. Laser drilling, plating, and patterning are available for making via-holes and circuit traces (No. 4 step). A cross section of a discrete thin capacitor in a PWB corresponding to after No. 3 step is shown in Figure 5.

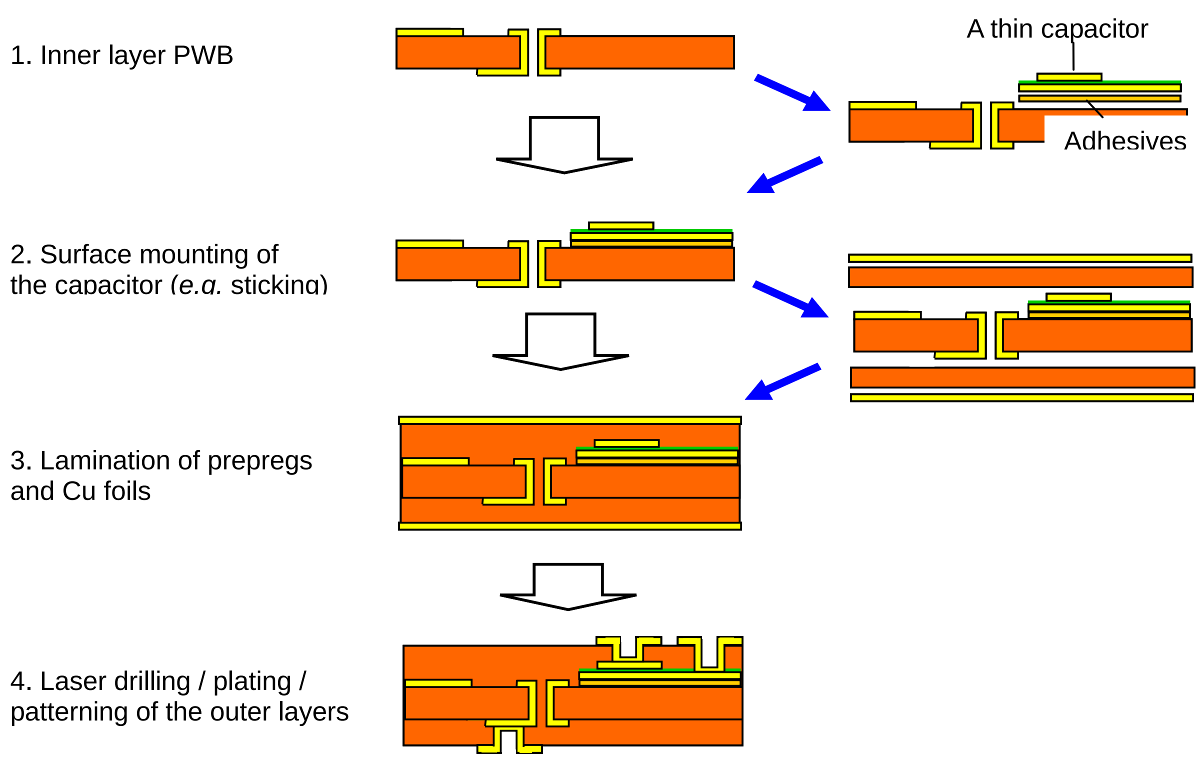

Figure 4 – Process flow of manufacturing PWB with an embedded thin capacitor

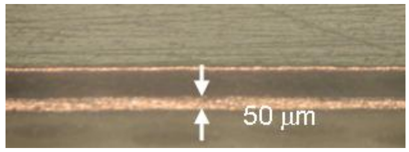

Figure 5 – Cross section of PWB with an embedded thin capacitor

Properties of the capacitor

We measured the high-frequency properties of the capacitor with the testing instruments listed in Table 1. Figure 6 shows the temperature dependence of capacitance and tan at 1 MHz. Because upper electrode size was 1 mm x 1 mm, the capacitance density was calculated at approximately 1 nF/mm^2. The capacitance shift between 25^{o}C and 85^{o}C was less than 3% and was very small. The tan shifted by over twofold in this temperature range, but the value was still under 1%. Figure 7 shows the upper-electrode area versus capacitance at room temperature; the relationship seems linear. By the way, although we tried to measure the capacitance at 100 mm^2, our equipments failed, probably because of the resonance failure of the measurement system. Improvement of the measurement technique is the next problem. Anyway, our thin capacitors proved to have enough capacitance to be applied as decoupling capacitors.

Table 1 – Test instruments for high-frequency property measurement

Item	Maker	Type
Vector network analyzer	Agilent	8753ES
Probe	Cascade	ACP40 GS650
Probe station	Alessi	REL-4500

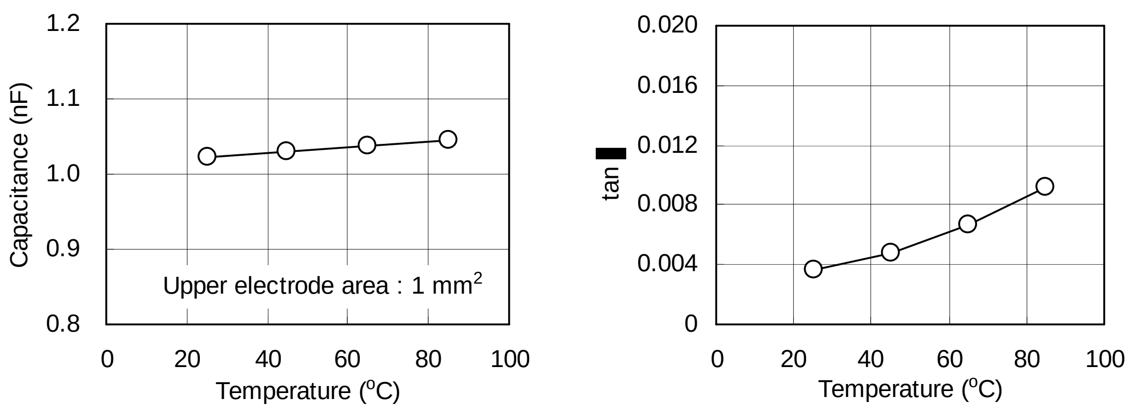

Figure 6 – Temperature dependence of capacitance and tan

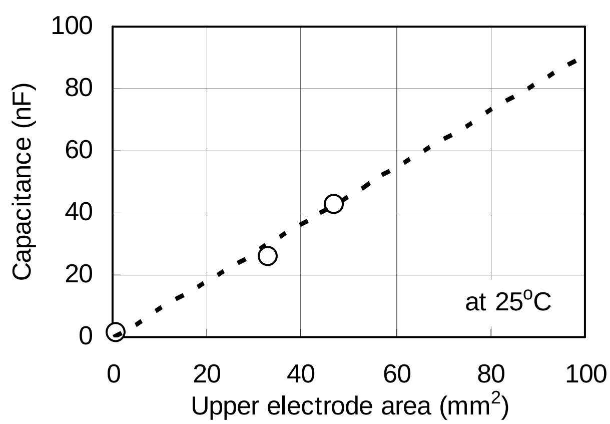

Figure 7 – Electrode area dependence of capacitance

Figure 8 shows the frequency dependence of the impedance of 1 nF capacitors: the red, bold line is for a discrete thin capacitor and the blue, lightface line for a 0603-size chip capacitor (GRM033R71C102 of Murata Manufacturing Co., Ltd.). In the range below 100 MHz, their impedance values were almost the same. However, their resonant frequencies, which were indicated as the minimal impedance point, were different with each other. The resonant frequency of the discrete thin capacitor was higher than that of the chip capacitor, indicating that former is more suitable for high-frequency usage.

We also measured the leakage current of the discrete thin capacitors. Figure 9 shows the leakage current density as a function of applied dc voltage. The leakage current at 4 V was about 1 nA/mm^2 and the breakdown voltage was over 20 V.

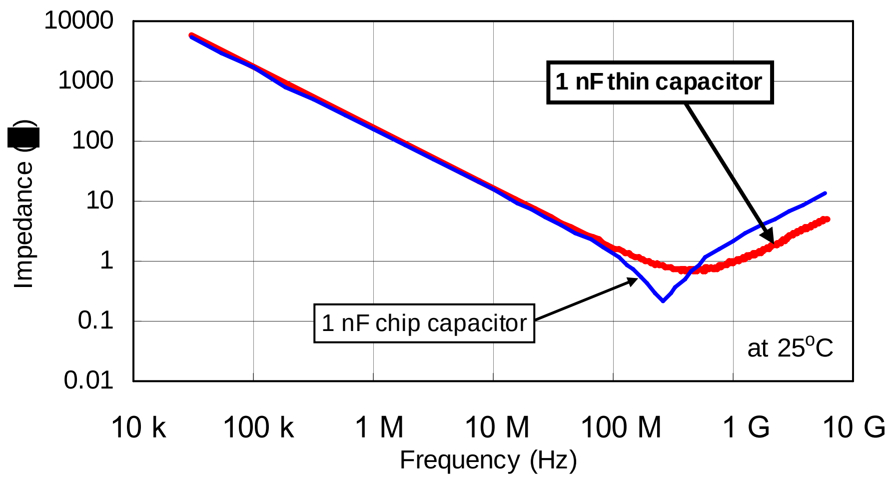

Figure 8 – Frequency dependence of capacitor impedance

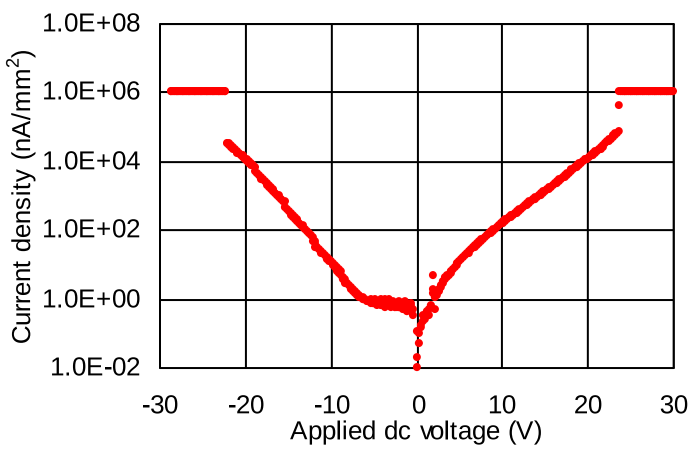

Figure 9 – Applied voltage dependence of leakage current density

Reliability was also evaluated as shown in Table 2. The discrete thin capacitor was able to keep the initial values of capacitance and leakage current after the heat resistance test of reflow lead-free soldering (260°C maximum, 3 times pass), dielectric strength test (10 V dc application for 5 s), electrostatic discharge resistance test (IEC/EN 61000-4-2 LEVEL 4), and temperature cycle test (500 cycles with no bias between -65°C and 125°C).

Table 2 – Results of reliability tests

Test item	Condition	Before test		After test	
		Capacitance (nF)	Leakage current (nA)	Capacitance (nF)	Leakage current (nA)
Heat resistance test of reflow lead-free soldering	260°C maximum, 3 times pass	1.15	20.1	1.12	7.0
				No change in appearance	
Dielectric strength test	10 V dc application for 5 s	1.10	13.2	1.10	19.0
Electrostatic discharge (ESD) resistance test	IEC/EN 61000-4-2 LEVEL 4	1.06	14.7	1.07	15.1
Temperature cycle test	500 cycles with no bias -65°C ↔ 125°C	1.01	10.2	0.98	0.3

Upper electrode area of the discrete thin capacitor was 1 mm^2. Capacitance was measured at 25°C, leakage current at 4 V, 25°C.

Conclusions

There are many merits in embedding thin decoupling capacitors in PWBs. We have developed a novel thin material having a MIM structure, whose insulator thickness is less than 0.5 m. In addition, the insulator is a lead-free material. Since the thickness of the capacitor made from our MIM material is limited to be less than 50 m, the capacitors can be embedded in PWBs with additional only one step in the process, which is to attach the discrete thin capacitors on boards with adhesives. We also have made a prototype of discrete thin capacitors from the MIM material and measured electric properties and reliability. The capacitance was as large as 100 nF and enough to be applied as decoupling capacitors. The resonant frequency of the discrete thin capacitor was higher than that of the conventional chip capacitor. This result will predict that the embedded thin capacitor is superior in the high-frequency usage. The reliability such as heat resistance proved satisfactory.

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