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Novel Material having Low Transmission Loss and Low Thermal Expansion designed for High Frequency Multi-layer Printed Circuit Board Applications

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Abstract

A new multi-layer PCB (printed circuit board) having low transmission loss and low thermal expansion that meets up-coming further high speed and high volume data transmission demands was developed. New modified polyphenylene ether (PPE) resin that posses excellent dielectric as well as thermal properties (Tg>200ºC) has been successfully designed and developed in house. The selection of a PPE backbone structure let us realize low Dk and low Df of the PCB, resulting in lower transmission loss. Low CTE of the PCB was achieved by incorporating inorganic fillers, while keeping low Df. By using special VLP copper foil, high-speed data transmission performance was improved significantly. The Dk, and Df of the developed PCB is 3.4-3.6, <0.002(1GHz) respectively and CTE in z direction is 45-50ppm. These are the basis of our development. We demonstrated about 50 % reduction in transmission loss in comparison to FR-4. Because of its low CTE, the PCB indicated excellent through-hole reliability. Over 2000 cycles of reliability were observed in its heat cycle (T/C; -65ºC to 125ºC) test. It was 4 times better performance than that of FR-4. The PCB showed high CAF resistance as well. No distinct failure was observed within 300 hours in its HAST (110ºC/85%/50V). Accordingly, newly developed our PCB has reliable performance. The PCB is compatible with the conventional PCB manufacturing process. Thus, we believe our newly developed PCB will offer one of the most promising solutions to achieve ultra high speed signal transmission technology that will play a very important role in the emerging era.

Introduction

In recent years, the high speed transmission of large volumes of information has been required primarily in the field of high-quality animations and others, and the frequency of transmitted signals has steadily been increasing[1), 2)]. As the speed and frequency of the transmission signals increase, materials with low dielectric constant and dissipation factor have been required for the making of printed circuit boards (PCBs). Furthermore, in order to process a large volume of information, the substrate tends to be formed with increasing numbers of layers. And in order to secure the continuity and reliability of the through-holes, the multi-layer sheet material must satisfy the requirement for reduced low thermal expansion. We have therefore developed a new multi-layer PCB material that can support rapid high-volume transmission and ensure reduced transmission loss and improved transmission speed in the high-frequency region. In addition to the aforementioned features, the multi-layer PCB, for which this material is used, provides high through-hole connection reliability due to its small thermal expansion coefficient. Furthermore, the newly developed multi-layer PCB provides a high Tg and is capable of accommodating lead-free soldering. Also, since the multi-layer lamination can be formed at temperatures of 200°C or lower, the newly developed PCB achieves superb process-ability.

Material for Printed Circuit Boards

For the base resin of MEGTRON6 (hereinafter called the “developed product”), namely a new multi-layer material for the printed circuit board (PCB) recently developed, modified polyphenylene ether (PPE) resin developed in-house is used[3)]. Table 1 shows the copper-clad laminate performance of the developed product and shows that when compared to conventional FR-4, the developed product provides truly outstanding dielectric properties, thermal expansion coefficient, and heat resistance. The next positive finding was the reduction of the dielectric dissipation factor (Df) to about 1/2 and the thermal expansion coefficient to about 3/4 when compared to MEGTRON5, the low dielectric constant material we originally developed. Moreover, other properties of the developed product as well as the dielectric dissipation factor and thermal expansion coefficient were found to be equivalent or superior to “MEGTRON5.” Referring now to Figure 1 to 3, the dielectric property of the developed product will be explained in further detail. The dielectric property was measured using the resonance method. A measurement method conforming to IPC TM-650 2.5.5.5 was adopted and measurement was carried out in the frequency range of 1 to 10 GHz. For the measuring apparatus, Hewlett Packard’s Network Analyzer 8519 was used. Figure 1 shows the frequency dependency of the dielectric property. Since the developed product was designed to include fewer polar groups in the material, the frequency dependency of Df is smaller than FR-4 and our previous products. Next, the temperature dependency of Dk and Df is shown in Figure 2. It was found that the temperature dependency of Dk and Df is extremely small, since the developed product provides a markedly high Tg. Lastly, Figure 3 shows the Dk and Df changes in terms of moisture absorption. The moisture absorption conditions are 85°C and 85%.

Table 1 – Copper Delaminate Performance of the Developed Product

Test Items	Test Conditions	Unit	Treatment Conditions	Developed product	(Rf.) FR-4	(Rf.) MEGTRON5
Volume Resistivity	-	Ω· cm	C-96/20/65	2.0×10^{16}	5.0×10^{15}	1.6×10^{16}
	-	Ω· cm	+C-96/40/90	1.0×10^{16}	1.0×10^{15}	4.7×10^{15}
Surface Resistivity	-	Ω	C-96/20/65	7.9×10^{13}	5.0×10^{14}	4.7×10^{13}
	-	Ω	+C-96/40/90	8.9×10^{12}	1.0×10^{14}	8.2×10^{12}
Insulation Resistivity	-	Ω	A	4.0×10^{14}	1.0×10^{14}	2.3×10^{14}
	-	Ω	D-2Hr/100℃	3.1×10^{13}	1.0×10^{13}	2.9×10^{13}
Dk	1GHz (IPC TM-650 2.5.5.9)	-	A	3.6	4.4	3.6
Df		-	A	0.002	0.015	0.004
Z-CTE	TMA	ppm/℃	A	47	65	60
Tg	DMA	℃	A	210	155	195
Solder Resistance	260℃ float	sec.	A	>120	>120	>120
PCT Solder Resistance	121℃2H + 260℃20s dip	-	-	OK	OK	OK
Heat Resistanse (1H)	Normal Copper 35μm	℃	A	270℃	240℃	270℃
Peel Strength	Normal Copper 35μm	kN/m	A	1.4	1.7	1.2
Water Absorption	-	%	E-24/50+D-24/23	0.20	0.10	0.36
Inflammability	UL94	-		V-0	V-0	V-0

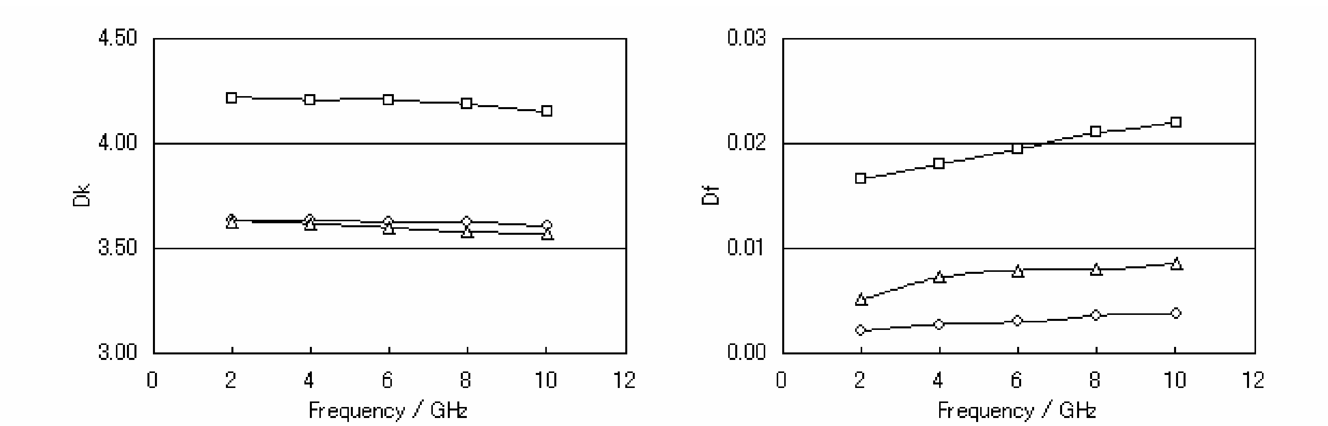


Figure 1 - Frequency Dependency of the Dielectric Property - The Circle is Developed Product, the Triangle is our previously Developed Product and the Square is FR-4

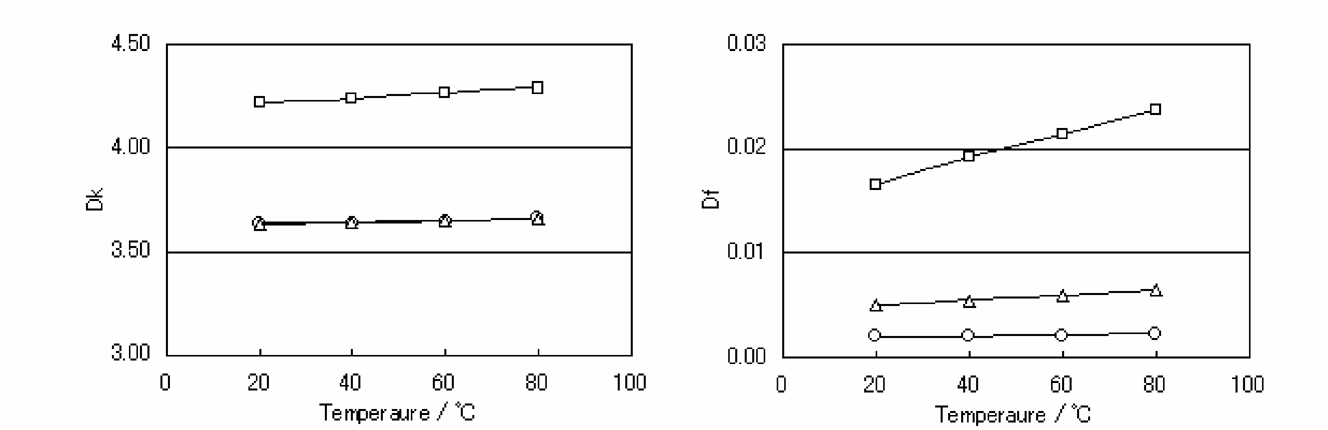


Figure 2 - Temperature Dependency of Dk and Df - Circle is the Developed Product the Triangle is our previous Product and the Square is FR-4

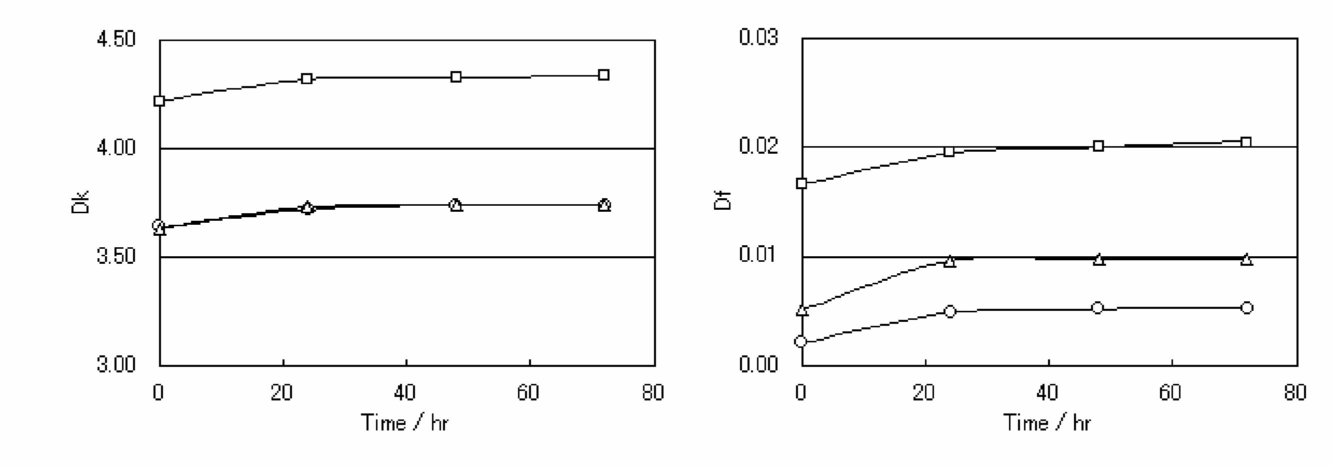


Figure 3 - The Drifts of Dk and Df with Moisture Absorption - Circle is the Developed Product the Triangle is our Previous Product and the Square is FR-4

It indicates that changes of Dk and Df due to moisture absorption are saturated over a 24 hour period for all the materials. In addition, the drifts of Dk and Df with moisture absorption are equal or exceed the performance of Our previous products. As described above, the developed product achieves outstanding dielectric properties. Finally, I would like to discuss the heat resistance of the developed product. As shown in Table 1, the Tg of the developed product is 200°C or higher, and satisfactory soldering heat resistance and general heat resistance has been achieved. Figure 4 shows temperature dependency of the copper foil and inner copper peel strength. The evaluation was carried out using 35-μm-thick normal copper foil. For the inner copper layer, an inner-layer roughening treatment (multi-bond process: MacDermid) was carried out. The copper foil peel strength of the developed product is lower than FR-4 at room temperature but at 200°C, the developed product provides a copper foil peel strength nearly double to that of FR-4. In addition, it was also found out that similar to the copper foil peel strength, the inner layer copper peel strength maintains adhesive qualities at 200°C. As described above, the developed product provides a high level of heat resistance and we are certain that it will be compatible with upcoming lead-free soldering processes.

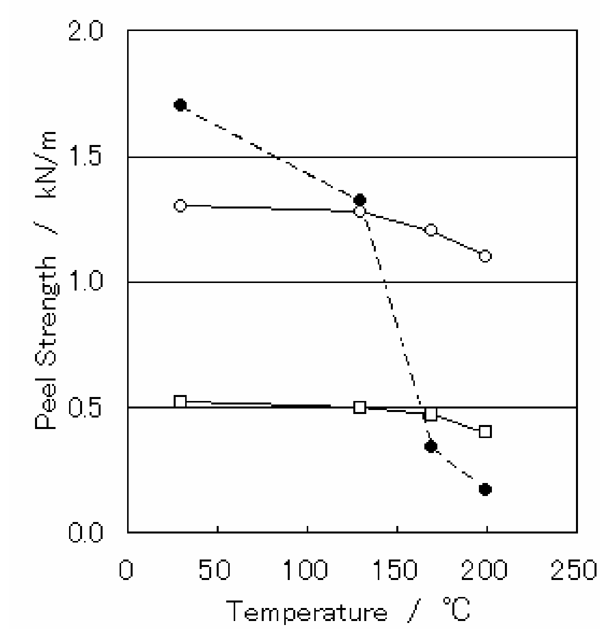


Figure 4 - Temperature dependency of the copper peel strength - Open Circle is the Developed Product (Normal Copper Foil), the Closed Circle is FR-4 and the Square is Inner-Copper Peel Strength of Developed Product

Process-ability of Printed Circuit Board

Now I would like to talk about the multi-layer formability required for fabricating printed circuit boards.

The press working conditions are shown in Figure 5 and the developed product can be formed under general-purpose pressing conditions of a 190°C forming temperature and 3-MPa forming pressure. The developed product was formed under reduced pressure for 30 minutes once heating had started. The multi-layer sheets fabricated under these conditions underwent a boiling solder test (involving first boiling for 6 hours, then being dipped in solder at 260°C for 20 seconds), and the multi-layer sheets came through without problem and exhibited satisfactory multi-layer properties.

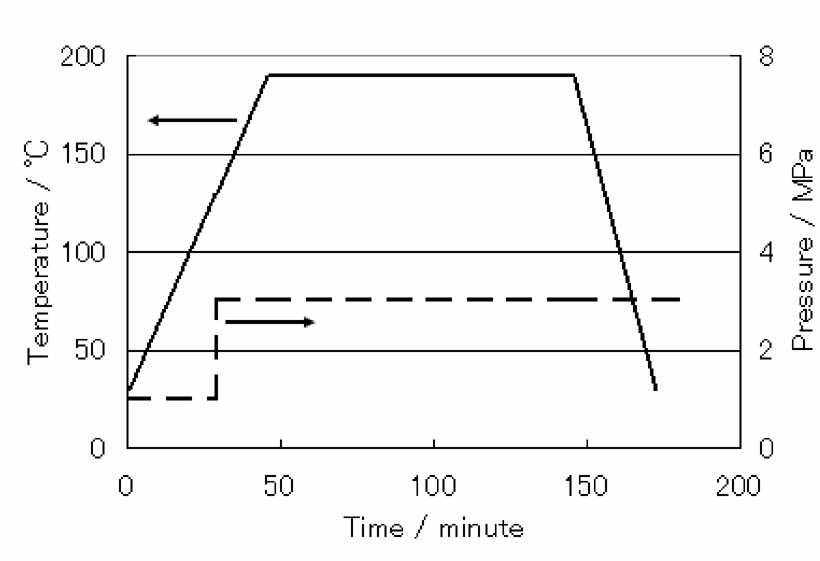


Figure 5 - Press Conditions

Reliability

First of all, I would like to talk about the through-hole connection reliability.

The substrate used to evaluate the through-hole connection reliability was 2.0 mm thick including through-holes of 0.3 mm in diameter with 15-µm-thick plating and a daisy chain pattern of 160 holes. The temperature cycle conditions conformed to the IPC standard and were -65°C for 30 minutes on the low-temperature side and 125°C for 30 minutes on the higher side. In the event that the percentage change in conductive resistance increased by 10% or more, the developed product was rejected. Figure 6 shows the evaluation results of the through-hole connection reliability. As seen in Figure 6, in case of FR-4, failure starts to occur at around 600 cycles and all of the test vehicles fail at 900 cycles. On the other hand, the developed product caused no trouble even after 2500-cycle processing, indicating that a connection reliability more than four times superior to that of FR-4 is achievable with the developed product. Our previous product, however, which is uses a resin system similar to that of the developed product, began to fail from 1500 cycles onwards. Consequently, it was concluded that the improvement of through-hole connection reliability could be attributed to the low level of thermal expansion.

I'd like to turn now to the insulation reliability evaluation results of PCB, using the developed product.

The test was performed using evaluation patterns with a total of 100 holes lined up in parallel, namely, 50 through-holes 0.25 mm in diameter at wall intervals of 0.4 mm lined in a longitudinal direction and 50 in a lateral direction respectively, on 0.75 mm-thick double-sided substrate. As shown in Figure 7, under the THB (85°C, 85%, 50V) conditions, the PCB developed no trouble even after 1000 hours and exhibited satisfactory insulation reliability. Under the HAST (110°C, 85%, 50V) conditions, the PCB operated trouble-free even after 300 hours. Since 100 hours of HAST conditions correspond to about 1000 hours of THB conditions, the developed product can be seen to provide a truly excellent level of insulation reliability, with results shown in Figure 8. As described above, the high reliability of the material for the developed product has been confirmed.

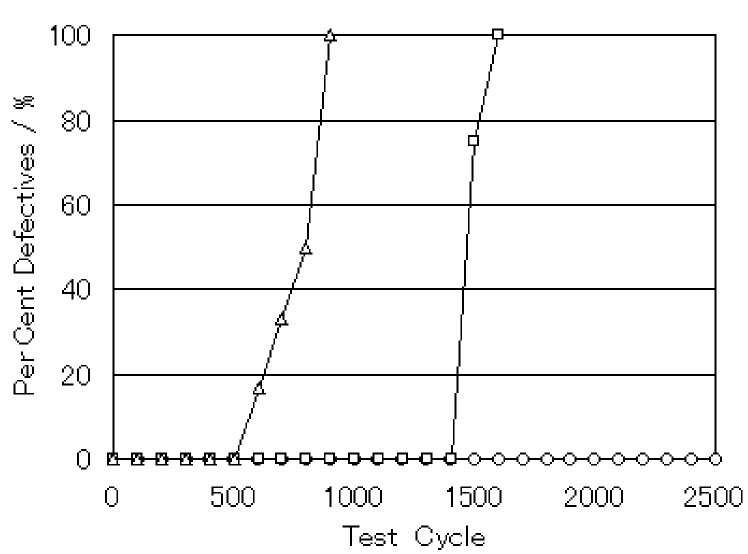


Figure 6 -The evaluation Results of the Through-Hole Connection Reliability – the Circle is the Developed Product, the Triangle is our Previous Product and the Square is FR-4

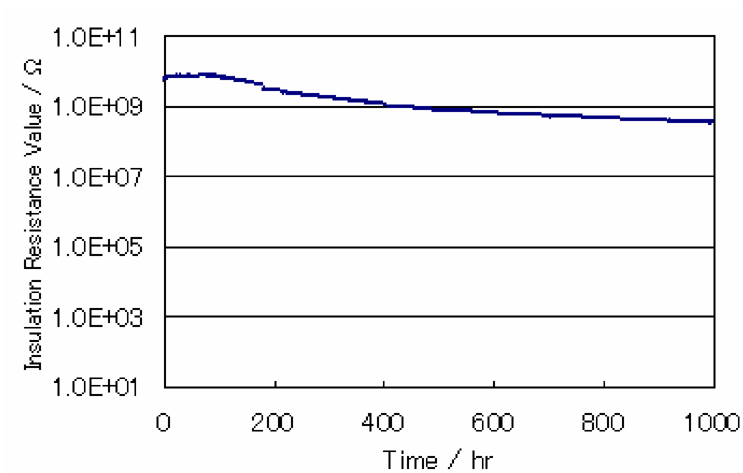


Figure 7 - Insulation Reliability under the THB (85ºC, 85%, 50V) Conditions

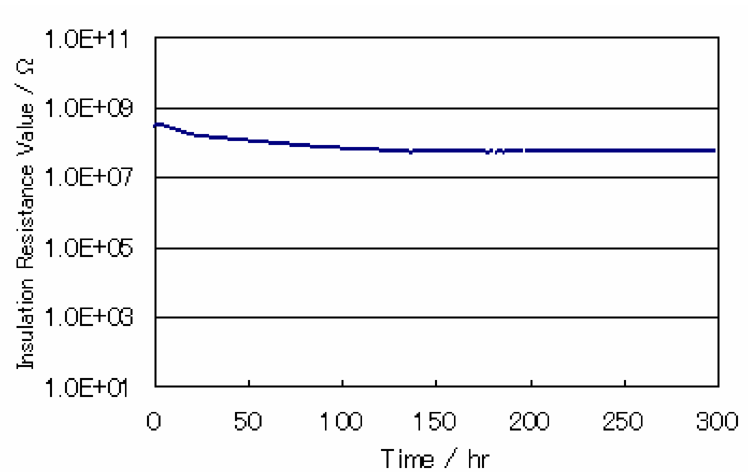


Figure 8 - Insulation Reliability under the HAST (110ºC, 85%, 50V) Conditions

Transmission Characteristics

Now, I'd like to talk about the evaluation of the low transmission loss, which is one of the key characteristics of the developed product.

For the evaluation substrate, the 3-layer printed circuit board shown in Figure 9 was used. The transmission loss was measured using an Agilent network analyzer model 8753E. First of all, using three types of copper foil of varying surface roughness as shown in Table 2, the relationship between the roughness of the copper foil surface and transmission loss was evaluated. The Rz of each copper foil was 7-8 μm for general foil, 3-4 μm for VLP foil, and 1-2 μm for special VLP foil (hereinafter called the "S-VLP foil"), respectively. The S-VLP foil provides an even lower profile than the VLP foil. Figure 10 shows the transmission characteristics results for various copper foils and as can be seen in the illustration, the smaller the surface roughness, the smaller the transmission loss. In particular, the S-VLP foil, with an Rz almost as flat as 1-2 μm, can be seen to reduce the transmission loss by about 30% as compared to general foil. Furthermore, the effects of the surface roughness were exhibited more conspicuously in the high-frequency region and it is assumed that this is attributable to the skin effect.

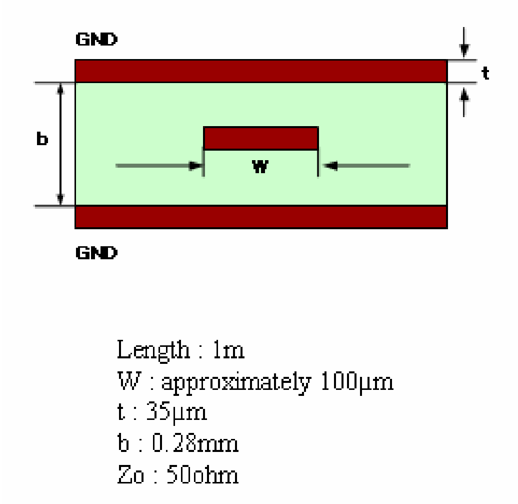


Figure 9 - Evaluation Substrate

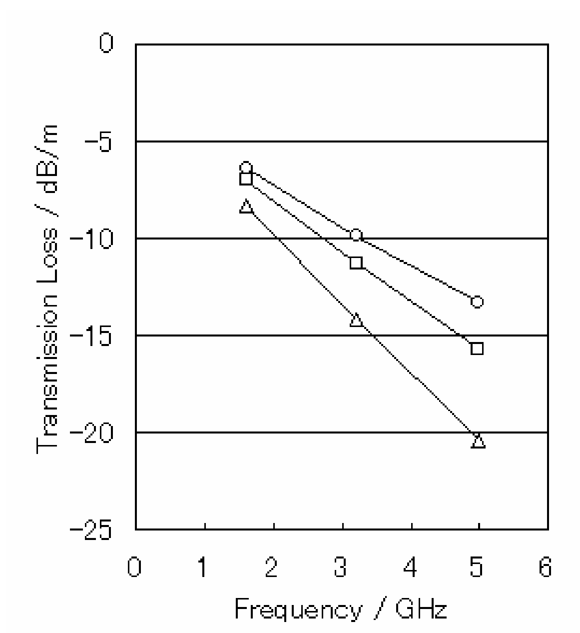
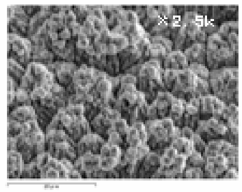
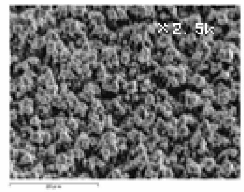
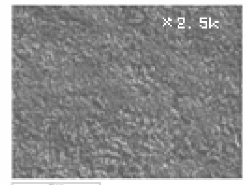


Figure 10 - The Transmission Characteristics results for Various Copper Foils – the Circle is S-VLP Copper Foil, the Square is VLP Foil and the Triangle Is Normal Foil

Table 2 – Three Types of copper Foil using Evaluation

Foil	Normal Copper Foil	VLP Foil	S-VLP Foil
The roughness shape of Mat side			
Rz(top-bottom)	6～8 μ m	3～4 μ m	1～2 μ m

Moving on now to Figure 11, this details the transmission loss of various materials. As shown in the illustration, the transmission loss of the developed product was reduced by over 50% as compared to the FR-4. The transmission loss is the sum of the conductive and dielectric losses as shown in Equation (1)[4].

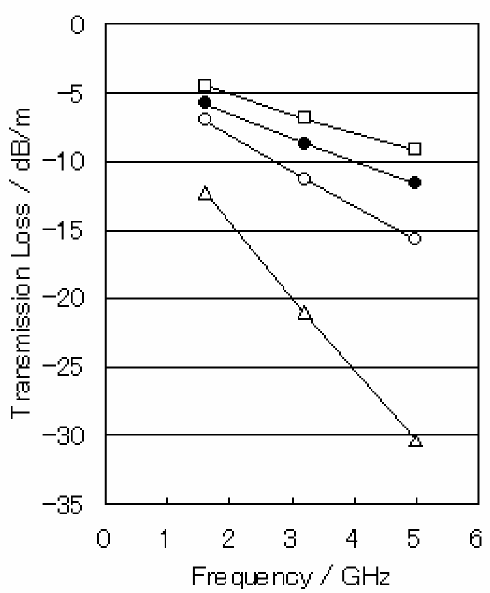


Figure 11 - Transmission Loss of Various Materials using VLP foil – the Circle is the Developed Product, the Square is our Previous Product and the Triangle is FR-4 - the Closed Circle is the Developed Product using S-VLP Foil and Low-Dk Glass Cloth

$$\alpha = \alpha c + \alpha d \text{ [dB/m]} \qquad (1)$$

Where, αc: Conductive loss, αd: Dielectric loss

$$\alpha c = \frac{0.0231 \times Rs \times \varepsilon r}{30\pi(b-t)} Z0 \left[1 + \frac{2 \times W}{b-t} + \frac{(b+t)}{\pi(b-t)} \ln\left(\frac{2b-t}{t}\right) + B \right] \quad \text{[dB/m} \qquad (2)$$

Where, εr: dielectric constant

$$Rs = \sqrt{\frac{\pi \times f \times \mu 0}{\sigma}} \qquad (3)$$

Where, f: frequency, μ0: magnetic permeability, σ: conductivity

$$B = \frac{[0.35 - (W/b)]}{(b-t)\times[1+12(t/b)]^2}\left[(t/b)\times(17.45b+35W)-9W+5.85-32.4(t^2/b)\right] \quad (4)$$

$$\alpha d = 27.3 \times \sqrt{\varepsilon r} \times \lambda 0^{-1} \times \tan\delta \quad [\mathrm{dB/m}] \quad (5)$$

Where, tanδ: dielectric dissipation factor

Figure 12 shows the transmission loss as calculated by the above equation. As shown in the illustration, the calculated and measured values respectively positively coincide. It also indicates that because FR-4 has a large Df and a considerable Df frequency dependency, an extremely large frequency dependency of dielectric loss is exhibited in the GHz band. In the vicinity of 2 GHz, the dielectric loss exceeds the conductive loss, indicating a large contribution of dielectric loss. On the other hand, the developed product and PTFE with a small Df make a small contribution to the dielectric loss in the GHz band. Consequently, it has been clarified that reducing the surface roughness of the conductor circuit is extremely useful in terms of reducing the transmission loss. Furthermore, because the reduction of Dk has an effect in terms of widening the circuit width in impedance matching in addition to the reduction of dielectric loss, the conductive loss can also be reduced. As described above, because the developed product has a small Df of the GHz band, it indicates that it also has an extremely small dielectric loss, as in the case of PTFE. If a low dielectric constant type glass cloth and S-VLP foil are used, the conductive loss can be reduced as well as the dielectric loss, indicating that the developed product exhibits a transmission loss comparable to the fluoro resin (PTFE) substrate.

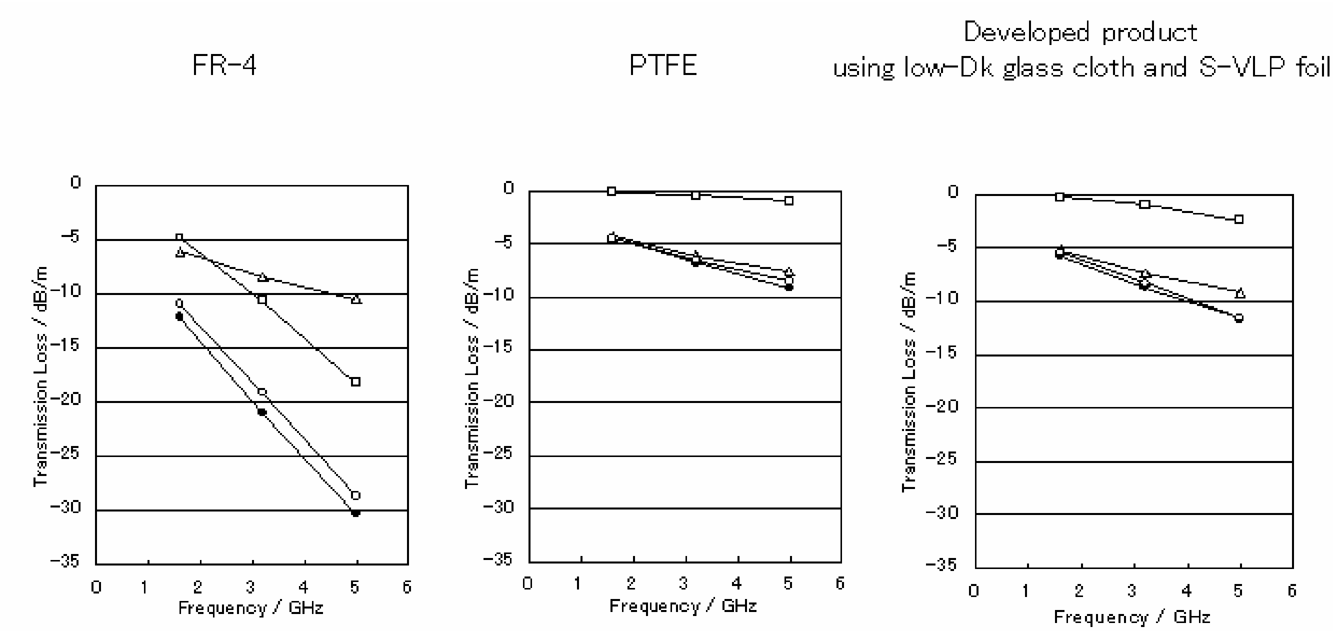


Figure 12 - The calculated transmission loss value - Circle is Transmission loss, square is dielectric loss and triangle is conductive loss - Closed circle is measured value of transmission loss

Conclusion

The authors have developed a new material for multi-layer PCB that can support rapid and high-volume data transmission with the aim of achieving a low transmission loss and improving the transmission speed in the high-frequency region. The present material is characterized by its small Dk and Df as well as superb transmission characteristics comparable to PTFE through the use of a low dielectric constant type of glass cloth and S-VLP foil. In addition, it has also been confirmed that the new material achieves high reliability due to its small thermal expansion coefficient and high Tg. The new material additionally provides outstanding multi-layer workability and it is assumed that the material for the new multi-layer PCB can meet upcoming demands in terms of further increased speed and volume of data transmission.

In future, we hope to meet still more stringent requirements in terms of improved reliability and process-ability achieved through a reduced dielectric constant, lighter and more compact products and increased layers. In so doing, we hope to contribute to the development of the upcoming information-oriented society.

References

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