Evaluation and Analysis Technologies for Printed Wiring Board Materials

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The printed wiring board (PWB) is a vital component of electronic equipment. Today, with product diversification and a shorter development cycle being dominant trends, it is essential to develop PWBs that satisfy performance and reliability requirements as quickly as possible. It has therefore become important to correctly select and appropriately use PWB materials that suit objectives from among the many commercially available materials. Over the last ten years, Fujitsu has been independently evaluating insulation materials for PWB use and has been comparing those results with the results of evaluating PWBs themselves while performing tests and accumulating data. We are currently developing evaluation technologies for determining whether new insulation materials can achieve the performance demanded of PWBs used in a variety of Fujitsu products. Among these technologies, we introduce ones that target thermomechanical properties, heat resistance, and transmission properties and mention their future directions.

1. Introduction

The printed wiring board (PWB) is an essential element in Fujitsu electronic equipment from ubiquitous compact terminals like mobile phones to large-scale supercomputers because it provides electrical connections between components and mechanical support for them. Many PWBs consist of alternating layers of copper wiring and resin-type insulation materials, so the properties of the insulation materials can affect PWB characteristics. The characteristics required of PWBs vary since electronic equipment can differ in application and format, and that is why various types of insulation materials are commercially available. Thus, to develop PWBs that satisfy the required performance and reliability in a relatively short time as demanded by today's short product development cycles, one must select materials that suit the objectives from the many commercially available materials and use them effectively.

The reference values published by material manufacturers have traditionally been used as an index for selecting materials, but this system is not without its problems as necessary information may not be provided and the properties listed may be only representative values that cannot be guaranteed. At the same time, PWBs are being required to have increasingly demanding characteristics and to satisfy specifications with even higher levels of accuracy.

Against this background, Fujitsu has been independently evaluating insulation materials for use in PWBs for more than ten years and has been comparing those results with the results of evaluating PWBs themselves to verify material performance and accumulate data. At present, Fujitsu is developing evaluation technologies that will let us ascertain whether new insulation materials can achieve the performance required of PWBs in diverse Fujitsu products. From among these, this paper describes ones targeting thermomechanical, heat-resistance, and transmission characteristics in insulation materials.

2. Thermomechanical characteristics

Since a PWB provides electrical connections between electronic components and simultaneously acts as a mechanical support for them, it is heated to the melting temperature of solder during fabrication. The insulating resin's coefficients of thermal expansion and elasticity change with temperature, and their values and the manner in which they change differ with the type of material. At the same time, copper, the material used for wiring in a PWB, generally exhibits fixed values and change behaviors, which makes it possible to predict PWB mechanical characteristics (change in dimensions and warping) by evaluating the insulation material. These days, PWB feature dimensions are shrinking and the mounting density is increasing, so to achieve secure component mounting and guarantee equipment reliability, one must control the change in dimensions and warping with an accuracy of a few micrometers. Accordingly, the absolute values obtained by measuring such physical quantities of insulation materials must be accurate. In general, thermomechanical analysis (TMA) is used to measure the coefficient of thermal expansion and dynamic mechanical analysis (DMA) is used to measure the elastic modulus.

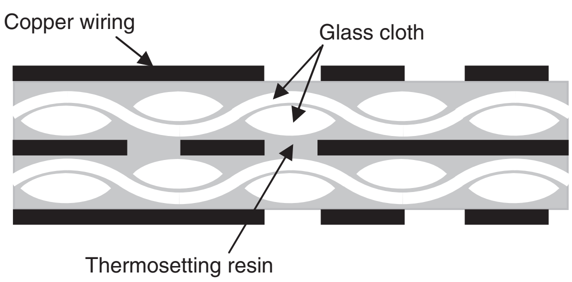

Figure 1
Cross section of PWB.

As shown in **Figure 1**, insulation material in a PWB is a composite consisting of glass cloth impregnated with thermosetting resin, so it is anisotropic; that is, its properties in the direction of the glass-cloth fibers (surface) differ from those in the thickness direction. Therefore, its coefficient of thermal expansion must be measured in both the surface and thickness directions.

Thermosetting resin does not melt even if the temperature is raised, but after hardening, its elastic modulus drops at temperatures above the glass-transition point (Tg). It is difficult to express this characteristic simply by determining the change in the elastic modulus, so it is necessary to evaluate its viscoelastic properties. The value of Tg is usually less than the melting temperature of solder, which makes it a critical property for predicting PWB characteristics. The most effective viscoelastic property evaluation technique is DMA, which enables simultaneous measurement of elasticity and viscosity by generating a periodic displacement. Tg can be determined from the maximum of tan δ (ratio of viscosity to elasticity).

In the viscoelastic property comparison shown in **Figure 2**, the elastic modulus for a general-purpose material is nearly constant up

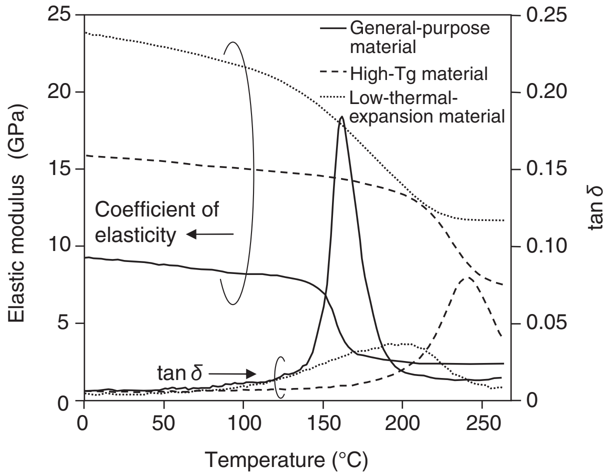

Figure 2
Viscoelastic properties of various materials.

to about 120°C, but it drops sharply near 150°C though it becomes constant once again after that. In high-Tg materials, in contrast, the temperature at which the elastic modulus drops is higher. Meanwhile, low-thermal-expansion materials have a higher elastic modulus than other materials. In this way, the mechanical properties of materials can be evaluated.

In addition, the change behavior and maximum value of tan δ are meaningful. Materials having a sharp peak and large maximum tan δ such as general-purpose materials are applied to PWBs that are required to be flexible to relieve the mechanical stress caused by mounting electronic components. On the other hand, materials like low-thermal-expansion materials having a broad peak and small maximum tan δ are considered to be suitable for PWBs that are required to be rigid with little temperature dependence in order to resist stress.[1)]

At Fujitsu, we are developing simulation techniques to investigate deformation (warpage) in PWBs subjected to heating. The technologies described above for evaluating the thermomechanical characteristics of materials by TMA and DMA are essential for improving simulation accuracy since they provide ways to obtain material property parameters. At the same time, we are working to improve warpage behavior evaluation accuracy by heating actual PWBs. All in all, these evaluation technologies are helping to achieve a significant improvement in the accuracy of warpage simulations.[2)]

3. Heat-resistance characteristics

Since a PWB is heated during the component mounting process, blistering may occur in the PWB if the heat-resistance characteristics of its insulation material are inadequate. Criteria for evaluating heat resistance with respect to blistering in PWBs have been specified by JEDEC.[note)] The cohesiveness of the wiring layer and the moisture absorption of insulation materials are considered to be factors in the occurrence of blistering and these properties are listed in insulation-material catalogs. However, we consider another factor to be just as important.

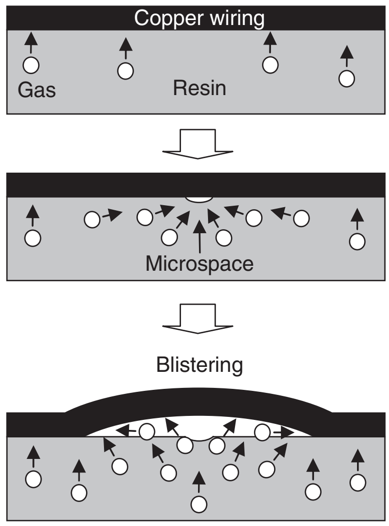

Figure 3
Mechanism of PWB blistering.

As shown in **Figure 3**, gas generated from the insulation material during heating concentrates in the microspace at the interface between the insulation material and wiring layer, giving rise to local exfoliation, which leads to blistering as it spreads along the interface. Gas generated by the heating of resin in this way can be evaluated by gas chromatography mass spectrometry (GC-MS). Outgassing profiles of different insulation materials are compared in **Figure 4**. The amount of gas generated increases with temperature, but the manner of the increase differs according to the type of insulation material. We can quantitatively compare what gases are generated at different temperatures and whether the amount of gas

note) JEDEC (Joint Electron Device Engineering Council): As an organ of the Electronic Industries Alliance, JEDEC develops standards for semiconductor technologies.

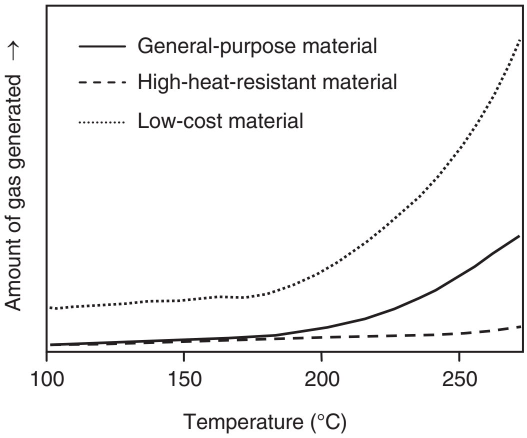

Figure 4
Outgassing profiles of various materials.

generated is large or small. Clearly, less gas is generated from a high-heat-resistant material than from a general-purpose material, and low-cost materials generate a large amount of gas even at low temperatures.

The results of evaluating blistering in PWBs using these materials on the basis of JEDEC heat-resistance evaluation criteria revealed that blistering occurs easily with large amounts of gas generated. This means that we can make general predictions about the heat resistance of a PWB even for new types of insulation materials by comparing their data with that of previously evaluated materials.

In addition, information about the gas generation temperature provides a basis for estimating the origin of that gas (additives, impurities in the material, thermally decomposed matter, etc.). Such information can be used not only for evaluating the heat resistance of insulation materials, but also as an index for evaluating PWB manufacturing processes and the technologies of board manufacturers and vendors.

4. Transmission characteristics

Signal-transmission speeds between components are becoming increasingly higher as equipment performance rises. The current demand is for signal transmission at frequencies in excess of 10 GHz. The main transmission characteristics of PWBs are considered to be the attenuation of a signal transmitted over a fixed distance (insertion loss) and the time required to transmit a signal over a fixed distance (propagation delay). These two transmission characteristics can be expressed as follows using relative permittivity ε and dielectric dissipation factor tan δ of the insulation material.

$$\text{insertion loss} \fallingdotseq k \times f \times \varepsilon^{1/2} \times \tan\delta$$
$$\text{propagation delay} \fallingdotseq \varepsilon^{1/2} / c$$
k: constant, f: frequency, c: speed of light

Accordingly, making the dielectric dissipation factor smaller should be effective for decreasing insertion loss and making the relative permittivity smaller should be effective for decreasing propagation delay. Although the relative permittivity and dielectric dissipation factor are provided as reference values of the electrical characteristics of insulation materials by material manufacturers, there is now a need to predict transmission characteristics with greater accuracy as higher speeds are sought.

The electrical characteristics of insulation materials have traditionally been measured using the static capacitor method specified by the Japanese Industrial Standards (JIS). However, in the frequency range above 1 GHz, there is a significant disparity between the results returned by this method and effective electrical characteristics during transmission.[3] Consequently, this method is inadequate for high-accuracy prediction of PWB transmission characteristics. From the start, electrical characteristics of insulation materials have served as a means of predicting insertion loss and propagation delay, but if transmission characteristics must now be determined more accurately, then actually measuring them would appear to be the most appropriate approach.

With this in mind, we decided to use a

method for measuring the insertion loss and propagation delay of a PWB by fabricating a simple wiring pattern (stripline structure) and applying a vector network analyzer to evaluate the electrical characteristics of insulation materials.[4] In actual measurements, we use a probe that can make measurements up to 40 GHz to minimize the effects of unnecessary elements such as the input/output structure and interlayer connection structure (via) in the evaluation of wiring-pattern transmission characteristics.

Measured and simulated results for insertion loss are compared in **Figure 5**. The measured results were obtained using a wiring pattern made of a general-purpose material and the simulated ones were obtained using the reference values of electrical characteristics as input to a standard circuit simulation program. As the signal frequency increases, the disparity between measured and simulated values increases with the actual insertion loss being greater than expected from the reference specifications.

Making actual measurements of transmission characteristics provides benefits beyond just evaluating the electrical characteristics of insulation materials. With this approach, a simple wiring pattern can also be used to evaluate the copper foil used as wiring material and the effects of the manufacturing process as well as the capabilities of PWB vendors.

Insertion losses (actual measurements) when different copper foils were used for wiring on the same PWB made of low-permittivity material are compared in **Figure 6**. At 5 GHz, there was a difference of several decibels between the two types of copper foils. This shows the importance of selecting appropriate copper foil to improve PWB transmission characteristics.

Simulation techniques using values obtained by actual measurements in the evaluation of transmission characteristics are also being developed.[4] If measured values of stripline transmission characteristics are available, they can be used to determine the electrical characteristics of insulation materials (relative permittivity and dielectric dissipation factor) by three-dimensional electromagnetic field analysis. The use of measured values in this way leads to high-accuracy transmission simulations that would not be possible using reference values. For example, to assess the effects of open stubs in through via holes in the structures shown in **Figure 7**, we compared the results of transmission simulations using an equivalent circuit for the via structure with the results of actual measurements using a PWB having the same structure (**Figure 8**). The simulation results agree well with actual measurements

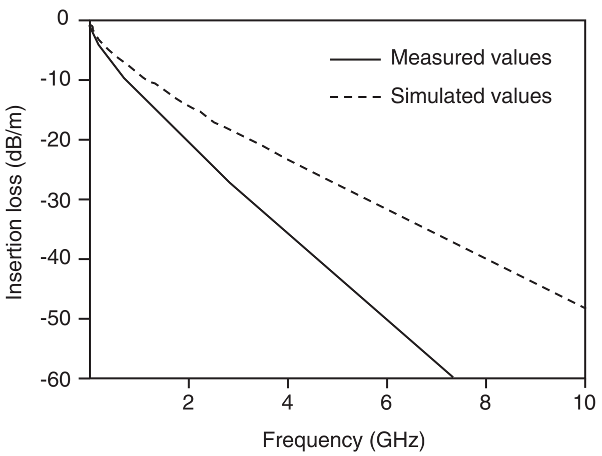

Figure 5
Comparison of measured and simulated insertion losses.

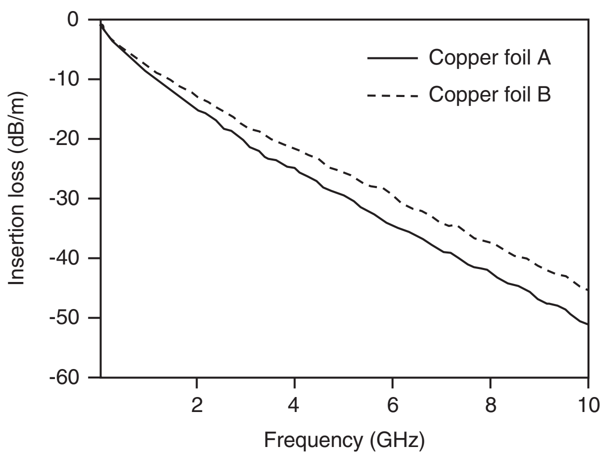

Figure 6
Effect of different copper foils on insertion loss.

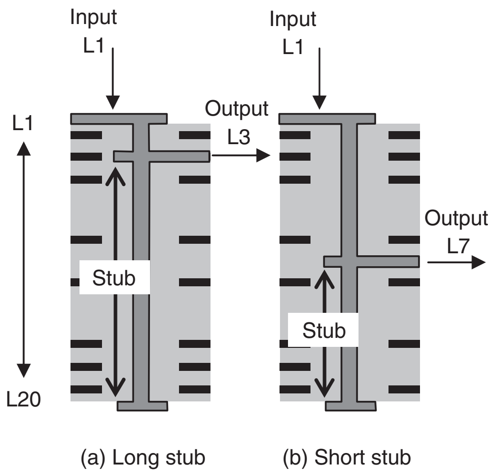

Figure 7
Cross sections of PWBs.

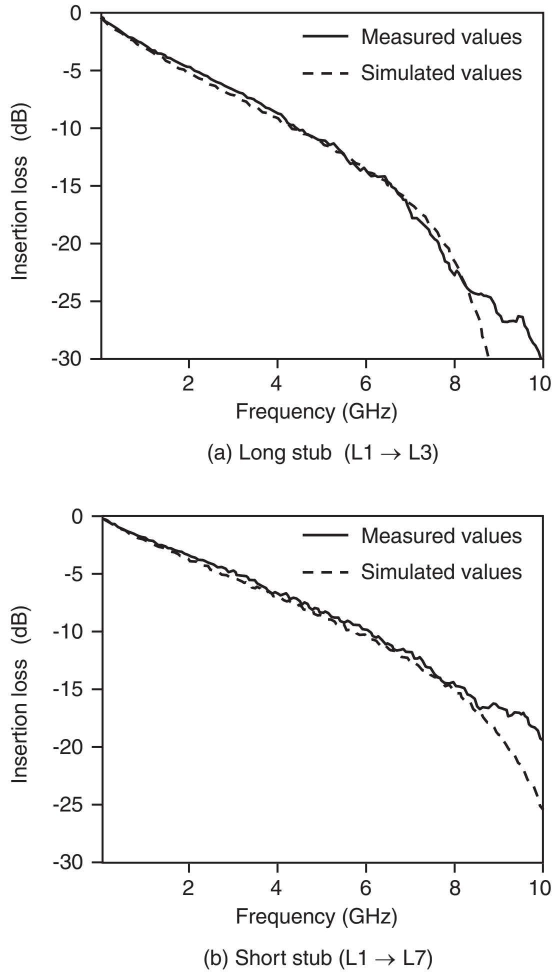

Figure 8
Comparison of measured and simulated insertion losses for through via holes with stubs.

up to about 8 GHz with a difference of less than 1 dB. This shows the validity of the equivalent circuit used in the simulation while also showing that evaluation using a simple wiring pattern can be an effective method for obtaining the electrical characteristics of insulation materials used in transmission simulations. We should be able to eliminate the discrepancy between simulated and measured values at high frequencies by revising the equivalent circuit or improving the measurement techniques.

Improving the simulation accuracy in the abovementioned ways can be viewed as an effective means of reducing the number of prototypes needed in product development. We can expect our technologies to help shorten development periods and reduce costs.

5. Conclusion

This paper examined the thermomechanical, heat-resistance, and transmission characteristics of insulation materials used in PWBs. As the demand for high-performance, diverse, and low-cost electronic equipment grows in the years to come, we can expect material manufacturers to propose a variety of new materials in addition to insulation materials for use in PWBs. The application of new technologies, however, has the potential to create new unforeseen problems. Under such conditions, evaluation technologies that can facilitate the selection and effective use of appropriate materials will become increasingly important.

The appearance of high-performance measurement equipment in recent years has made it possible to obtain a huge amount of information relatively easily. However, evaluation is not simply a matter of making measurements. One must begin by drawing up a plan based on objectives and the target material and performing measurements by sampling and continue by selecting which information obtained from measurements is necessary and performing tests. Evaluations can be done only by repeating this process, that is, by repeating measurements and by testing and accumulating experience. As such, evaluation technologies support the reliability of Fujitsu products.

References

1) D. Mizutani et al.: Application of Photosensitive Polyimide to Multichip Module (MCM-D). *Journal of Photopolymer Science and Technology*, Vol. 9, No. 2, pp. 323–331 (1996).
2) M. Kurashina: High-accuracy Prediction of Warping in Heated Semiconductor Packages. (in Japanese), Proceedings of the 15th Symposium on Microjoining and Assembly Technology in Electronics (Mate 2009), 2009, pp. 129–132.
3) T. Tajima et al.: Research of a Substrate Dielectric Constant using Circuit and Electromagnetic Field Simulation. (in Japanese), Proceedings of the IEICE General Conference, Vol. 2005, Electronics 2, 2005, p.18.
4) T. Yamada et al.: Development of Low-loss and Low-noise PWB Technologies. (in Japanese), *Technical report of IEICE*, Vol. 103, No. 646, pp. 73–76 (2004).

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