High Frequency Transmission Property Evaluation of Fine Wiring Substrates

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Abstract

This paper reports on an investigation of the fundamental transmission characteristics of the microstrip line in a Cu/BCB multi-layer fine wiring structure with a line width and space of less than 10 μm on a silicon core substrate. By measuring the S-parameter and analyzing the elemental contribution of the dielectric loss, we determined that BCB has better high frequency electrical characteristics than other dielectric materials. Transmission loss was divided into dielectric loss and conductive loss by theoretical fitting of the experimental results. The ratio of dielectric loss versus conductive loss obtained by our fitting analysis is in good agreement with that of our model. The following facts have been revealed: 1) Transmission loss is not greatly dependent on the width of fine wiring. 2) Much of the transmission loss depends on conductive loss caused by the skin effect. 3) When using low dielectric constant materials as the dielectric layer, conductive loss rather than dielectric loss dominates the transmission characteristics.

Keywords: Fine-Wiring Substrate, High Frequency Transmission Property, Conductive Loss, Dielectric Loss, Skin Effect.

1. Introduction

The purpose of this study is to evaluate the high frequency transmission characteristics of fine wiring packaging substrates. As electronic devices become smaller and more sophisticated and system operating speeds increase, packaging substrates increasingly require better high frequency characteristics. We have been developing a silicon interposer adapted to high frequency transmission, which has Cu/benzocyclobutene (BCB) multi-layered substrates and micrometer-width copper traces made by the sputter semi-additive method. According to the International Technology Roadmap for Semiconductors (ITRS),[1] chip-to-board signal frequency will exceed 10 GHz by 2015, while trace line/space in the substrate will decrease to less than 10/10 μm (see Table 1.)

Much attention has already been given to the high frequency characteristics of multi-layer packaging substrates. In this field, most studies have focused on printed wiring boards (PWB) which have wide line widths, thick layers, and extremely rough surfaces. Several studies have been conducted to evaluate the characteristics of Cu/BCB substrates for high-speed transmission,[2–4] but none has tried to verify the high frequency characteristics of fine wiring with widths of less than 10 μm. Very few studies of high frequency characteristics have focused on the trace cross-section shape effect and on the elemental contribution of transmission loss between conductor loss and dielectric loss. This study fills that research gap.

The high frequency transmission characteristics of the substrates are greatly influenced by factors such as the trace geometry (i.e., conductor line width, length, and thickness) and the electrical characteristics of the dielectric material. When the signal frequency surpasses 1 GHz,
the surface roughness of traces and the strict presence of
the skin effect also have a great effect on the high fre-
quency characteristics of the substrate. To verify the influ-
ence of these factors on the electronic characteristics, we
evaluated the high frequency transmission characteristics
of fabricated Test Element Group (TEG) substrates. The S-
parameter was used because quantitative data is easy to
get and analyze, and it shows appropriate high frequency
characteristics. The high frequency characteristics were
evaluated in two ways: measurement of the S-parameter
using a Vector Network Analyzer (VNA) and 3D electro-
magnetic simulation by the Finite Element Method
(FEM.)

2. TEG substrate fabrication

As demand for high density and integration increases,
higher process accuracy is needed, because even a slight
error between the designed and actual copper trace width
can result in characteristic impedance \(Z_0\) mismatching.
In the fabrication process of Cu/BCB multi-layer sub-
strates, the design rule (line/space) can be narrowed
down to the order of micrometers to produce high packag-
ing density. To provide feedback for this accurate fabrica-
tion process, the fundamental transmission characteristics
have been evaluated by the measurement and simulation
results described below.

2.1 Dielectric materials

Two important factors make a dielectric material suit-
able for high frequency transmission: low dielectric con-
stant \(\varepsilon_r\), and low dissipation factor \(\tan \delta\). In this paper,
two dielectric materials are discussed. The first is BCB,
which has advantages in terms of high-speed transmission
and low transmission loss, so it has potential in terms of its
high frequency characteristics. The second material is flu-
orene, which is a kind of epoxy acrylate and has good cost
performance. BCB has lower \(\varepsilon_r\) \((-2.65)\) and a much lower
dissipation factor \(\tan \delta = 0.0008\) at 10MHz) than the com-
monly-used polyimide \(\varepsilon_r = 3.2, \tan \delta = 0.002\) at 1 kHz). Flu-
orene has \(\varepsilon_r = 3.4, \tan \delta = 0.03\) (at 1MHz). Table 2 shows the
electronic characteristics of these two materials along with
commonly-used polyimide.

2.2 TEG substrate fabrication

A fine wiring substrate that has two metal layers on the
silicon core substrate has been fabricated. The cross-sec-
tional structure of the TEG is a microstrip line. Figure 1
shows top and cross-sectional views of the TEG. The first
metal layer for the ground (GND) was formed over the
entire substrate with copper. The second layer has fine
copper traces for the signal. The metal layer was formed
by first sputtering first Cr (300Å) and Cu (1700Å) as the
seed layer and then adding Cu plating by the semi-additive
method. As the dielectric material either BCB or fluorene,
as described above, was spin-coated on the GND plane
layer.

A total of three TEG lines are evaluated in this paper.
The designed line widths are 5, 7.5, and 10 \(\mu m\) and the
lengths are all 15mm. The thickness of the dielectric and
signal layers has been designed from the cross-section
structure so as to match to the 50 \(\Omega\) characteristic imped-
ance \(Z_0\) (described below in Section 3.1.)

3. S-Parameter measurement

3.1 Impedance matching

The characteristic impedance \(Z_0\) of the TEG should be
as close to 50\(\Omega\) as possible, otherwise an energy reflection
by impedance mismatching occurs at the contact point
between the probe and the TEG pad. This energy reflec-
tion usually causes an inaccurate S-parameter measure-
ment result (as shown in Figure 2). The cross-sectional
geometry of the microstrip line structure, such as line
thickness and width and the thickness of the dielectric
layer, largely determines the impedance matching in the
measurement system. To avoid impedance mismatching, it
is necessary to control the geometry during the pattern
design and process condition of the photomask pattern.

The characteristic impedance of a microstrip line is the-
oretically provided in Eq. (1),\[5\] where \(t [\mu m]\): trace thick-
ness, \(w [\mu m]\): line width, \(\varepsilon_r\): dielectric constant and \(h [\mu m]\):

### Table 2  Dielectric material electronic properties.

<table>
<thead>
<tr>
<th></th>
<th>Dielectric constant (\varepsilon_r)</th>
<th>Dissipation factor (\tan \delta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCB</td>
<td>2.65 (1 kHz-20 GHz)</td>
<td>0.0008 (1 MHz-1MHz)</td>
</tr>
<tr>
<td>fluorene</td>
<td>3.4 (1 MHz)</td>
<td>0.03 (1 MHz)</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3.2 (1 kHz-20 GHz)</td>
<td>0.002 (1 kHz)</td>
</tr>
</tbody>
</table>

Fig. 1  Top and cross-sectional view of microstrip line struc-
ture TEG. 'S' is the signal pad, 'G' is the ground pad.
thickness of the dielectric layer. Figure 3 shows the cross-sectional structure of the microstrip line. 'w', 't' and 'h' are the factors which determine the characteristic impedance of the fine trace.

\[ Z_0 = 87 \times \ln \left( \frac{5.99h}{0.8w + t} \right) \sqrt{\varepsilon_r + 1.44} \] 

(1)

For this study, the line widths (w) were first fixed to 5, 7.5, and 10 \( \mu \)m and the line thickness (t) to 5 \( \mu \)m. Next, h (of BCB or fluorene) was calculated by Eq. (1) so as to have \( Z_0 \) near 50 \( \Omega \). Because of slight process variations, the actual line widths (w) became a little wider and the thickness of the dielectric layer (h) thicker. This design for impedance matching was based on the \( w = 10 \mu \)m case, and because all the TEGs have the same thickness of copper and dielectric layer, so the calculated \( Z_0 \) for \( w = 7.5 \) and 5 \( \mu \)m have drifted away from 50\( \Omega \). When BCB is used, the desired \( h \) is 7.0 \( \mu \)m and calculated \( Z_0 \) is 50.31\( \Omega \). For fluorene, the desired \( h \) is 7.7\( \mu \)m and calculated \( Z_0 \) is 50.01\( \Omega \).

Calculation of \( Z_0 \) and measurement results of \( t \) and \( h \) are shown in Table 3. Analyzing the S11 parameter (reflection) enabled us to evaluate how much \( Z_0 \) deviated from 50\( \Omega \).

### Table 3 Impedance calculation results for each design.

<table>
<thead>
<tr>
<th>Design</th>
<th>Designed width (( \mu )m)</th>
<th>Measured width (( \mu )m)</th>
<th>( Z_0 ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCB</td>
<td>5.0</td>
<td>5.9</td>
<td>50.31</td>
</tr>
<tr>
<td>Fluorene</td>
<td>5.0</td>
<td>5.9</td>
<td>50.01</td>
</tr>
</tbody>
</table>

3.2 S-Parameter measurement equipment

The Vector Network Analyzer (VNA) Agilent 8722ES was used for S-parameter measurement. Calibration was done by the Short–Open–Load–Through (SOLT) method. The measured frequency range was from 0.1 to 20 GHz by 100MHz pitch. Both probes were GS/SG type Cascade Microtech ACP20-GS/SG200 which guarantee measurement results up to 18 GHz. Using this 2-port measurement system, the frequency characteristics of S11 and S21 were obtained. Port number 1 is the signal input side of the transmission line and number 2 is the output side. Thus, S-parameter S11 means the reflection element at the input port, while S21 represents the transmission element at the output port.

3.3 Transmission characteristic comparison using different dielectric materials

Figure 4 shows the measured S11 Smith chart of the TEGs with line widths of 5, 7.5 and 10 \( \mu \)m. Figure 5 presents the S21 parameter measurement results selecting
either BCB or fluorene as the dielectric material. The measured frequency range for both is from 0.5 to 20 GHz.

In Figure 4, the center point indicates $Z_0 = 50 \, \Omega$ ($R = 50, X = 0$ in $Z_0 = R + jX$). For BCB, the plotted data circularly curves more closely to the center point of the chart than the data for fluorene. The reason can be found in the fabrication results in Table 3, which indicate better impedance matching was achieved when BCB was used as the dielectric material than when fluorene was used.

Furthermore, looking at the transmission loss shown in Figure 5, BCB has almost the same result even if the wavering of the plot data slightly increases as the line width decreases. The resulting transmission loss was from -3.0dB up to 18 GHz. Comparing BCB and fluorene at each line width, the loss when using fluorene was worse than with BCB. The finer the line width, the greater the transmission loss.

For both BCB and fluorene, the finer the line width, the further the $S_{11}$ plot moves from the center point of the chart. This has a qualitative relation with the calculation results in Table 3. The frequency dependence plot of $S_{11}$ deorbits so much as to make $Z_0$ differ from 50$\,\Omega$

These results show that when using BCB, the width of the fine wiring does not depend greatly on the high frequency characteristic. In other words, BCB does not have much effect on the high frequency characteristic of fine wiring, so it enables the use of quite fine wiring as transmission lines in the substrate. This in turn broadens design flexibility and allows higher wiring densities.

### 3.4 Transmission loss elemental contribution analysis

This section discusses transmission loss. Transmission loss can be divided into two main elements: dielectric loss ($\alpha_d$) and conductive loss ($\alpha_c$). The magnitude of $\alpha_d$ depends on the kind of dielectric material. We have tried to quantitatively analyze how large a role $\alpha_d$ plays in total transmission loss, and to evaluate how good the effect of BCB is on the high frequency characteristic.

The way to divide the loss into the two elements above is to assume that all the loss ($\alpha = S_{21}$) consists of $\alpha_d$ and $\alpha_c$:

$$\alpha = \alpha_d + \alpha_c \quad (2)$$

$\alpha_d$ and $\alpha_c$ has the following proportionality relation with the signal frequency ($f$):

$$\alpha_d \propto f = A \cdot f, \quad \alpha_c \propto \sqrt{f} = B \cdot \sqrt{f} \quad (3)$$

where A and B are proportional constants. Eq. (2) can be modified as

$$\alpha / \sqrt{f} = A / \sqrt{f} + B \quad (4)$$

Thus plotting $\alpha / \sqrt{f}$ against $\sqrt{f}$ enables us to find the constant $A$, and the value $\alpha_d$ can be obtained by the fitting line using Eq. (3).

The measured $S_{21}$ data was divided into $\alpha_d$ and $\alpha_c$ elements for both BCB and fluorene when the line width was 10 $\mu$m. Figure 6 shows the fitting result for the case of BCB. The slope of the fitting line is -0.0314, which is equal to the constant $A$. $\alpha_d$ has the relation with the dielectric constant ($\varepsilon_r$)

$$\alpha_d = \sqrt{\varepsilon_r \cdot \tan \delta} \cdot f \quad (5)$$

From Eqs. (3) and (5), $\alpha_d$ is also expressed as

$$A = \sqrt{\varepsilon_r \cdot \tan \delta} \quad (6)$$

The calculated value $\tan \delta$ from Eq. (6) was 9.0e-4, which is quite near to the value in Table 2 (8.0e-4).

As Figure 7 indicates, the elemental contribution of $\alpha_d$ was 16% at 20 GHz when BCB was used as the dielectric material. In contrast, when fluorene was used (Figure 8),
the \( \alpha_d \) contribution for the same line width and length was 34\% at 20 GHz. The difference between 16\% and 34\% is evidently caused by the difference in the dielectric properties of the material. These results show that better electronic characteristics of the dielectric material enable suppression of the total transmission loss.

For the printed-wiring board (PWB), which has wide line widths and thick layers, dielectric loss is usually the major component of transmission loss.[6] The results described above show, however, that the main part of the total loss is not dielectric loss but rather conductive loss. It is likely that this reversal of elemental contribution is primarily caused by the excellent electronic characteristics of BCB and the finer wiring length than on the PWB. To confirm this in detail, the following 3D electromagnetic simulation was performed.

4. Electromagnetic simulation analysis

4.1 Model and condition of simulation

S-parameter calculation by electromagnetic simulation was performed using the 3D model shown in Figure 1. Ansoft HFSS ver8.5, which utilizes the Finite Element Method (FEM), was used for the simulation. The material parameters used for the dielectric material in this model are as shown in Table 2: copper (\( \sigma = 5.76 \times 10^7 \) [S/m]) for the trace and GND layer, BCB (\( \varepsilon_r = 2.65, \tan\delta = 8.0 \times 10^{-4} \)), and fluorene (\( \varepsilon_r = 3.4, \tan\delta = 3.0 \times 10^{-2} \)). The atmosphere around the model was set as air.

First, all meshes were generated based on the 20 GHz frequency electromagnetic field, and refined only inside the copper trace for the skin effect. Then a sweep analysis in the frequency range from 0.5 to 20 GHz was performed. Data obtained for \( S_{11} \) and \( S_{21} \) were used, as in the experimental measurements.

Fig. 8  Plot of divided loss (\( \alpha \)) of 15mm-length and 10 \( \mu \)m-width fine wiring when using fluorene as the dielectric material. The dielectric loss (\( \alpha_d \)) has 34\% ratio to the total loss (\( \alpha \)) when a 20 GHz-signal passes in the wiring. \( \alpha_d \) contribution is more than twice as the result of BCB.

Fig. 9  Electrical field distribution comparison by whether solving inside copper or not. If solved inside, simulated \( S_{21} \) has been in good agreement with measured transmission loss.

Fig. 10  Skin depth (\( \delta \)) of copper versus applied signal frequency where \( s \) is the conductivity of copper and \( m \) is the permeability in vacuum. At 20 GHz, \( \delta \) reaches less than 0.5 \( \mu \)m.

The advantage of considering the skin effect is clearly shown in Figure 9. The skin depth has the value shown in Figure 10 when the material is copper. The cumulative intensity distribution of the electrical field in the copper trace indicates the presence of the skin effect. When the generated meshes included the copper trace, the obtained data better agreed with the measurements.

4.2 Transmission loss elemental contribution analysis

The contribution of the dielectric loss to total transmission loss was evaluated from the simulation results in the same way as described in Section 3.4. To approach the value of \( \alpha_d \) and \( \alpha_c \) separately, two hypothetical models were considered. For calculating \( \alpha_d \), we have used model (b) in Figure 11, in which a perfect conductor (\( \sigma = \infty \)) was substituted for copper as the trace and GND material. For calculating \( \alpha_c \), model (c) was considered, in which the dielectric material was air (\( \varepsilon_r = 1.0, \tan\delta = 0.0 \)) as an ideal dielectric layer, instead of BCB.

The simulation results are summarized in Figure 12. In this evaluation, total loss was calculated by using the model shown in Figure 11 (a). Compared with Figure 7, \( \alpha_d \) has similar contribution percentage for the total loss at 20 GHz (12\%). This result indicates the evaluation of \( \alpha_d \).
elemental contribution was achieved well, and that the hypothetical models shown in Figure 11 are useful for the electrical contribution analysis of total transmission loss.

4.3 Trace surface roughness effect on transmission loss

When the signal frequency is within the GHz range, the skin effect occurs and resistance of the conductor trace increases. As Figure 9 indicates, the skin depth becomes smaller and smaller as the frequency goes up. The skin effect occurs at the trace surface; therefore it is possible that trace surface roughness has an effect on transmission loss.

Figure 13 shows the simulated $S_{21}$ results when the surface roughness changes from 0.0 to 2.0 $\mu$m (in RMS units). HFSS calculates the surface resistance that results from the skin effect. As the plot shows, there is no effect on transmission loss when the surface roughness has been increased to 0.1 $\mu$m. The trace surface roughness of the fabricated substrate has been measured and it is less than 0.1 $\mu$m. Thus it is shown that surface roughness of the trace has little effect on transmission loss when using our sputter semi-additive method, compared to conventional printed wiring boards which have almost 2.0 $\mu$m surface trace roughness in order to obtain a high peel strength of the copper foil wiring to the prepreg resin. In this case, the transmission loss increases approximately 1dB at 20 GHz, which also is shown in Figure 13.

4.4 Trace cross-section shape effect on transmission loss

For the cross-sectional structure of the fine-wiring, it is desirable to keep the same width between the top and bottom edges of the trace. In the common subtractive wiring formation process, however, overetching usually causes the actual cross-section shape of the trace to usually form into a trapezoid. A comparison analysis by simulation was performed to determine whether this cross-section shape change affects the high-frequency transmission loss of the wiring.

Figure 14 shows measured transmission loss and the simulated results for three cross-sectional copper trace shapes. Results vary among the shapes in the high frequency range over 5 GHz. There is an about 0.6 dB difference between the 'No taper' and 'More tapered' types at 20 GHz.
as the dielectric material. In the simulation results, ‘No taper’ refers to the model of the perfect rectangular cross-sectional shape of the trace which will be obtained by our semi-additive process. The ‘Tapered’ model has the cross-section shape nearest to that of the fabricated fine-wiring. The ‘More tapered’ model covers the occurrence of over-etching.

Below than 5 GHz range, these three simulated results are almost the same. Gaps begin to appear gradually over 5 GHz and there is an approximately 0.6dB gap at 20 GHz between the ‘No taper’ and ‘More tapered’ models. It can be said that the cross-section shape has a fairly strong effect on high frequency transmission loss.

A gap in the trace cross-section structure appears to affect high frequency transmission loss due to the presence of the skin effect. The skin effect has an absolute relation with the total cross-section edge length. The more tapered the trace cross-section becomes, the smaller the total cross-section edge length of the trace and the more impedance mismatching tends to occur.

It can be also concluded that the semi-additive forming process for wiring (mentioned in Section 2.2) has an advantage over the commonly used subtractive process when it comes to getting good high frequency transmission properties.

5. Conclusions

1) The high frequency transmission characteristics of a microstrip line with a width of less than 10 μm has been evaluated using S-parameter measurement and 3D electromagnetic simulation. As a result, it was clearly revealed that the dielectric material BCB has better high frequency characteristics than fluorene.

2) BCB, which has little effect on the high frequency characteristics of fine wiring, enables the use of quite fine wiring for transmission lines in the substrate, broadening design freedom and enabling the use of higher wiring density.

3) Through an elemental contribution analysis by both measurement and simulation, the quantitatively low rate of dielectric loss of BCB has been quantitatively verified.

4) A hypothetical simulation model has been shown to be effective for evaluating the division of transmission loss into dielectric loss and conductive loss, and the results are in good agreement with measured data.

5) It has been verified by electromagnetic simulation that the trace surface roughness of the substrate from using the sputter semi-additive method does not have an effect on high frequency transmission loss.

6) The cross-section shape of the fine wiring has a fair effect on the transmission loss. For obtaining good high frequency transmission properties, the semi-additive forming wiring process is more favorable than the common subtractive process.

References


