Copper Foil Technology for High-Frequency Applications

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Introduction

Advances in information/communications technology are transforming the Internet from a medium for searching for information into a medium for providing and receiving various types of information and services. As the number of users and the variety of services continue to grow, there are increasing demands for a more comfortable environment--an environment that allows "quicker on-demand access to more information, which is presented with better realism." In order to make such an (Internet) environment a reality, we need to be able to exchange a large amount of information within a short space of time. This in turn makes it necessary to accelerate signal speed, or to increase the signals frequency.

Printed wiring boards used for handling high-frequency signals are required to have lower levels of transmission loss so as to maintain and ensure signal quality. From the viewpoint of copper foil, which provides the basis of conductive trace, the main concerns are as follows: (1) increases in conductor loss (one of the factors behind transmission loss) and (2) declines in bonding strength to resin (declines in trace bonding strength) resulting from reductions, (which is intended for minimizing dielectric loss), of the dielectric constants and dissipation factors of substrates.

This paper discusses the findings of our examination of the issues above.

Reduction of Conductor Loss

Transmission loss consists of three factors, namely, conductor loss, dielectric loss, and radiation loss (see Figure1).

Of these factors, conductor loss relates directly to copper foil and becomes greater at higher signal frequencies because of increased skin resistance. At higher frequencies, an electric current tend to run through the surface of a conductor due to the skin effect (passing an alternating current through a conductor changes the magnetic flux around it, creating a back electromotive force in the core of the conductor, making the current flow difficult). This effect reduces the effective cross-sectional area through which an electric current passes, thus increasing resistance. This is what is called skin resistance. The "skin" of a conductor through which an electric current passes is expressed as "skin depth," which varies inversely with the square root of the frequency. Shown in Figure 2 are the relationships among skin resistance, skin depth, and frequency. Using the equation shown in Figure 2, we calculated skin depth and skin resistance at several different frequencies. At signal frequencies in the GHz range, skin depth dropped to 2 µm or less, indicating that signals passed only through the surface/skin of a conductive trace.

We then studied the influence of copper foil, the basis of conductive trace, on conductor loss. As shown in Figure 3, we observed that at higher frequencies (frequencies in the GHz range), different types of copper foil had different levels of transmission loss. VLP foil ("VLP" stands for "very low profile") exhibited a lower level of transmission loss compared to standard foil (middle-profile foil). We also found that this gap in transmission loss became wider with increasing frequency. It actually became as wide as 2 dB/m at 5 GHz. This is because the skin effect increased signal propagation distance on middle/high-profile foil at higher frequencies. For confirmation, we prepared measurement circuits (resonance circuits) using copper foils (each 18 µm thick) having several different levels of bonded-surface roughness (profiles) and then measured their Q factors. The results are shown in Figure 4. As the graph indicates, copper foil having lower profiles exhibited higher Q factors, or better transmission characteristics (smaller transmission loss).

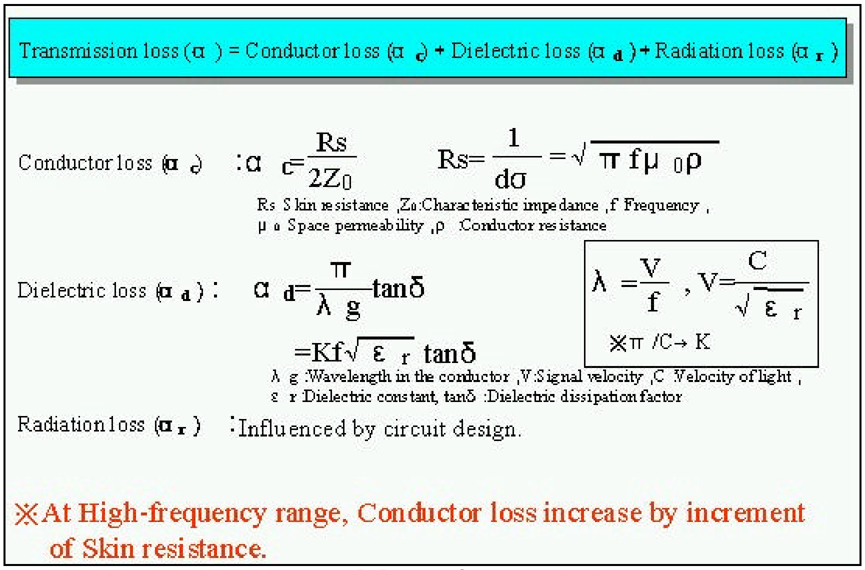


Figure 1 – Breakdown of Transmission Loss

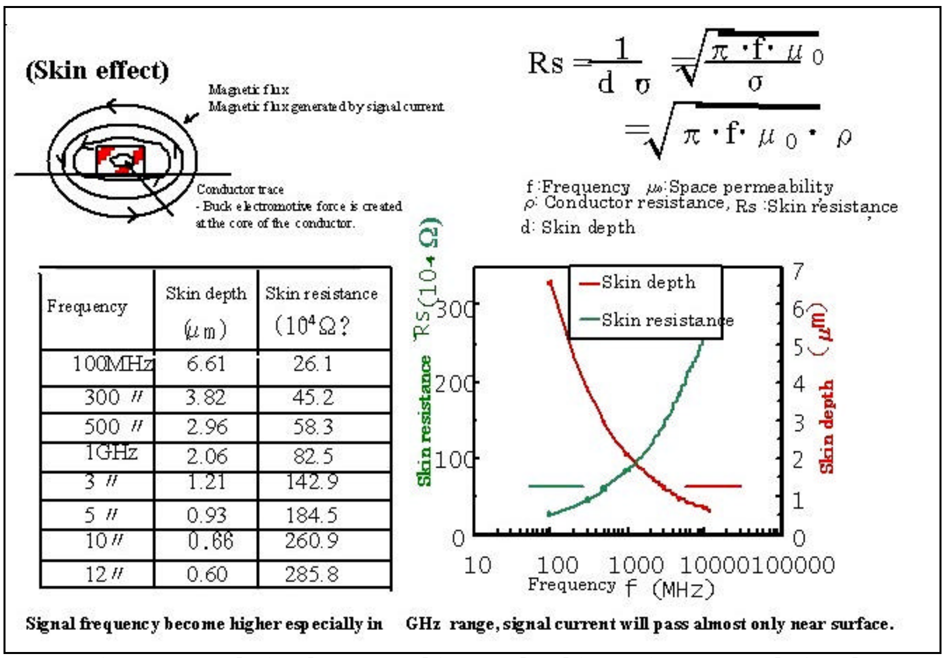


Figure 2 – Relation between Skin Depth, Skin Resistance, and Signal

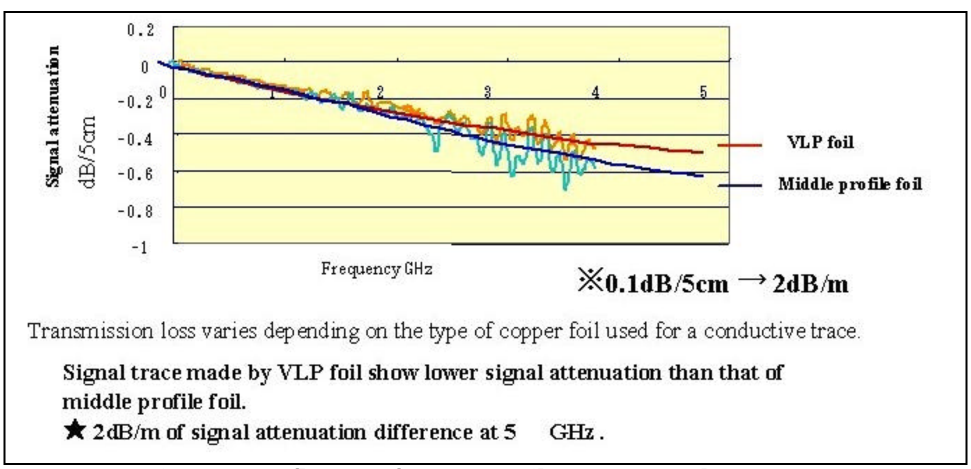


Figure 3 – Influence of Copper Foil Type to Conductor Loss

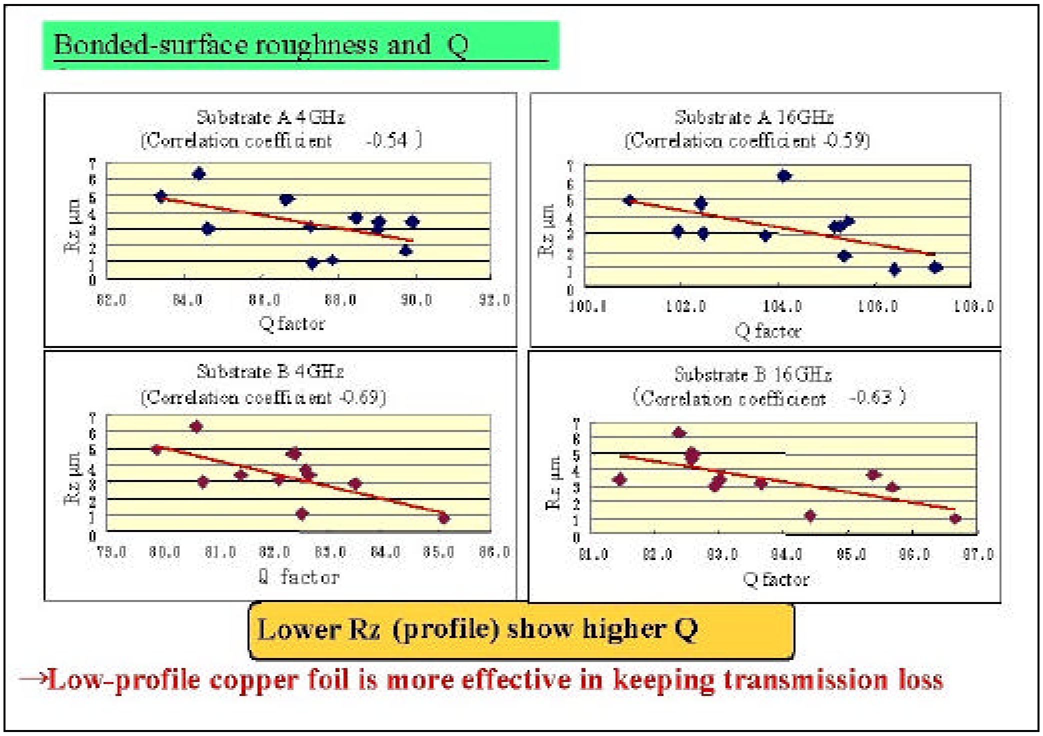


Figure 4 - Relation between Copper Foil Bonded-Surface Roughness (Profile) and Q

Our findings with respect to copper foil and transmission loss are summarized as follows.

(1) Skin resistance becomes greater with increasing signal frequency, which causes increase in conductor loss.

(2) In the high-frequency (GHz) range, transmission loss varies depending on the type of copper foil used for a conductive trace.
   - Low-profile copper foil is more effective in keeping transmission loss small.
   - Middle/high-profile copper foil may/will present problems concerning their mat side, such as signal attenuation and signal delay owing to increased propagation distance.

As can be seen from the above, low-profile copper foil will be indispensable for ensuring signal transmission at higher signal frequencies, especially in the GHz range.

Improvement of the Bonding Strength to High-Frequency Substrates

Improvement of Adhesion to Resins having a Low Dielectric Constant and a Low Dissipation Factor

Another factor behind transmission loss is dielectric loss. Dielectric loss depends on the dielectric constant and dissipation factor of substrate resin. Passing a pulse signal through a trace causes the electric field around the trace to change. As the cycle of this electric field change (frequency) becomes closer to the relaxation time of resin's polarization (the transition time of charged objects causing polarization), a lag arises in electric displacement (d: the angle of the lag in electric displacement). In such a situation, molecular friction generates inside resin, creating heat, which results in transmission loss. Resins used for high-frequency substrates therefore contain fewer (or in fact no) substituents with high polarity so that electric field changes does not cause polarization easily.

Meanwhile, such high-polarity substituents contribute significantly to the chemical adhesion between resin and copper foil (see the illustrations in Figure 5). Resins containing fewer (or no) high-polarity substituents to reduce their dielectric constants and dissipation factors adhere less securely to copper foil. This makes it difficult to achieve the desired circuit (trace) peel strength. We conducted an experiment to compare the peel strength and bonding failure mode between standard FR-4 substrate and a substrate with a low dissipation factor (Df) as shown in Figure 6. The FR-4 substrate had a cohesive failure (its bonding was broken inside resin), demonstrating a high level of peel strength. In contrast, the LowDf substrate had a boundary failure (its bonding was broken at the boundary of copper foil and resin), showing very low level of peel strength. Such a low level of peel strength can cause circuits to peel off in the process of manufacturing printed wiring boards or lead mounted devices on outermost layers to come away.

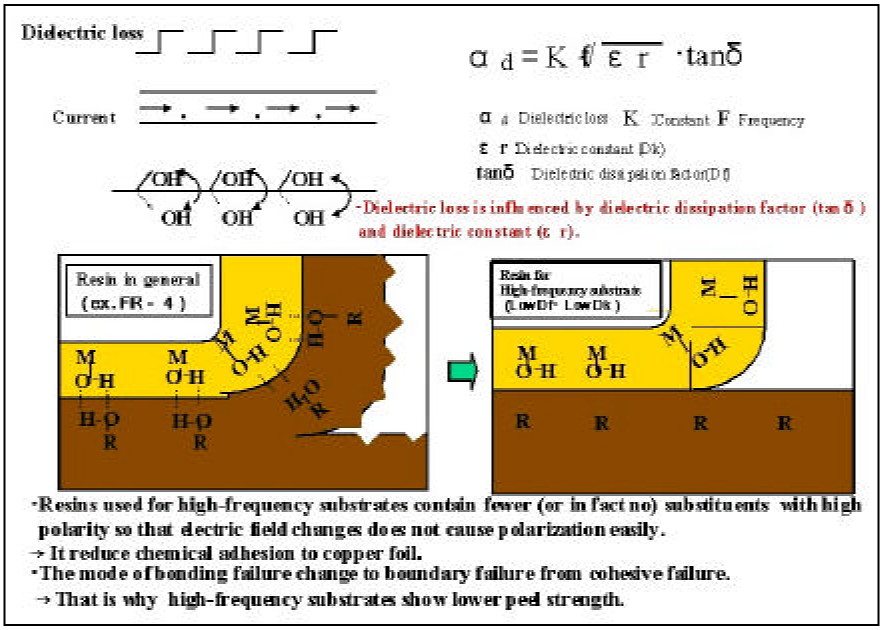


Figure 5 – Adhesion between Copper Foil and Resin for High-Frequency

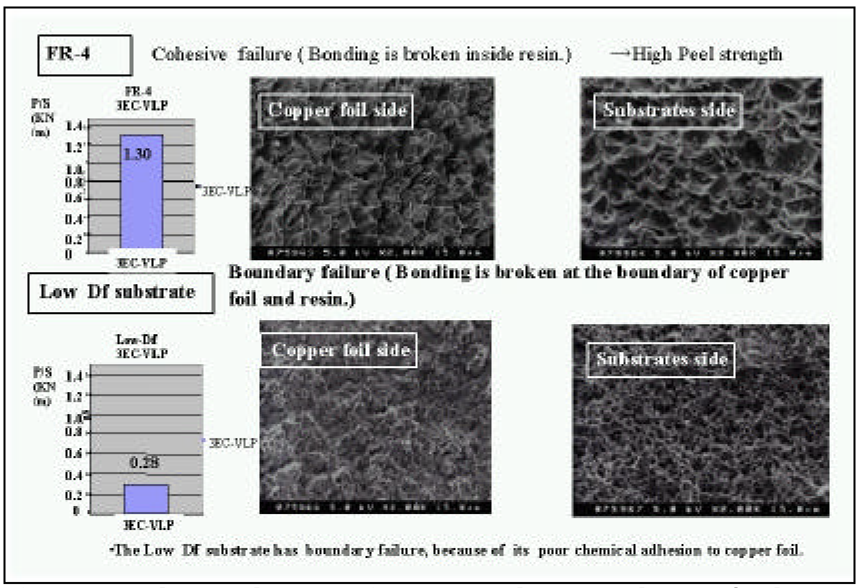


Figure 6 - Peel strength Comparison FR-4 Substrate and Low Df Substrate

Using high-profile copper foil improves peel strength, but as described earlier, it increases transmission loss. Therefore, high-profile copper foil is not suitable for high-frequency substrates. The peel strength to high-frequency substrates must be improved without compromising the high-frequency property of conductive trace ; meaning that, with bonded-surface profiles kept low. This is why we attempted to improve adhesion to high-frequency resin by providing copper foil surfaces with minute copper particles ("Micro nodule"). The “Micro nodule" increased copper foil's surface area (the surface area bonded to resin) without changing its profiles, and made it easier for resin to stick firmly.

As shown in Figure 7, the addition of Micro nodule to copper foil surfaces changed the mode of bonding failure to "cohesive," improving peel strength significantly. In addition, we found that the added Micro nodule produced no deterioration in transmission loss.

Bonding Strength

The peel strength of low-profile copper foil is inevitably lower than that of high-profile copper foil. This might lead some to have doubts about the reliability of component mounting used for surface-mounted board. For this reason, we performed tests and comparisons using three criteria, namely, peel strength (by peeling circuits/trace away), pull strength (by pulling pads upward), and shear strength. (by pushing over a pads). We found that in cases of cohesive failure, peel strength is influenced by copper foil profiles, but not pull strength and shear strength (see Figure 8).

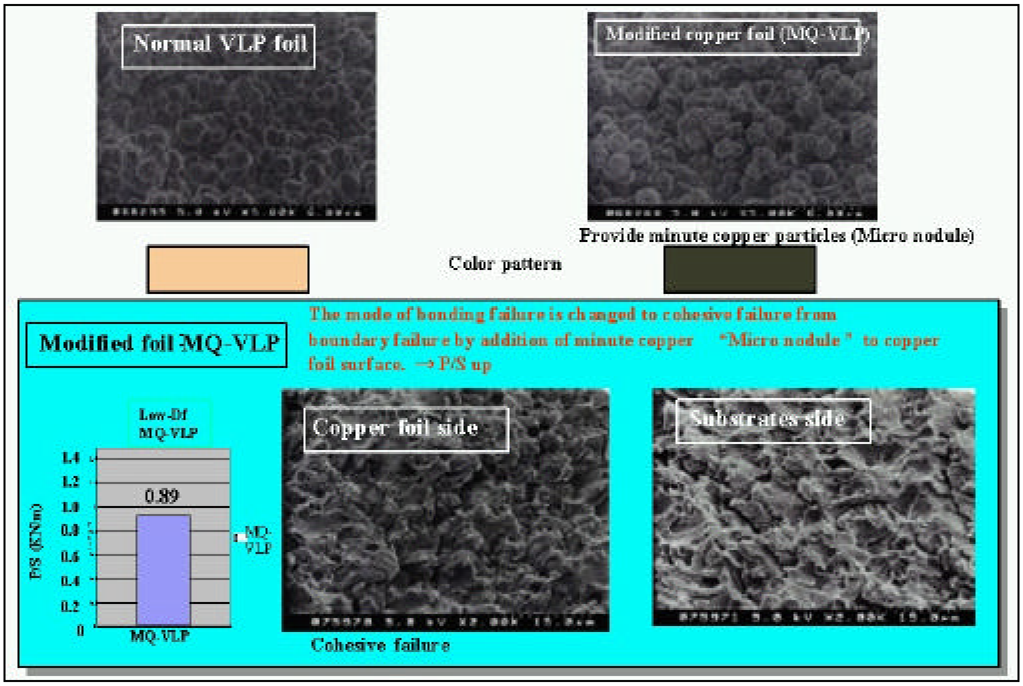


Figure 7 – Peel Strength Improvement at High-Frequency Substrate

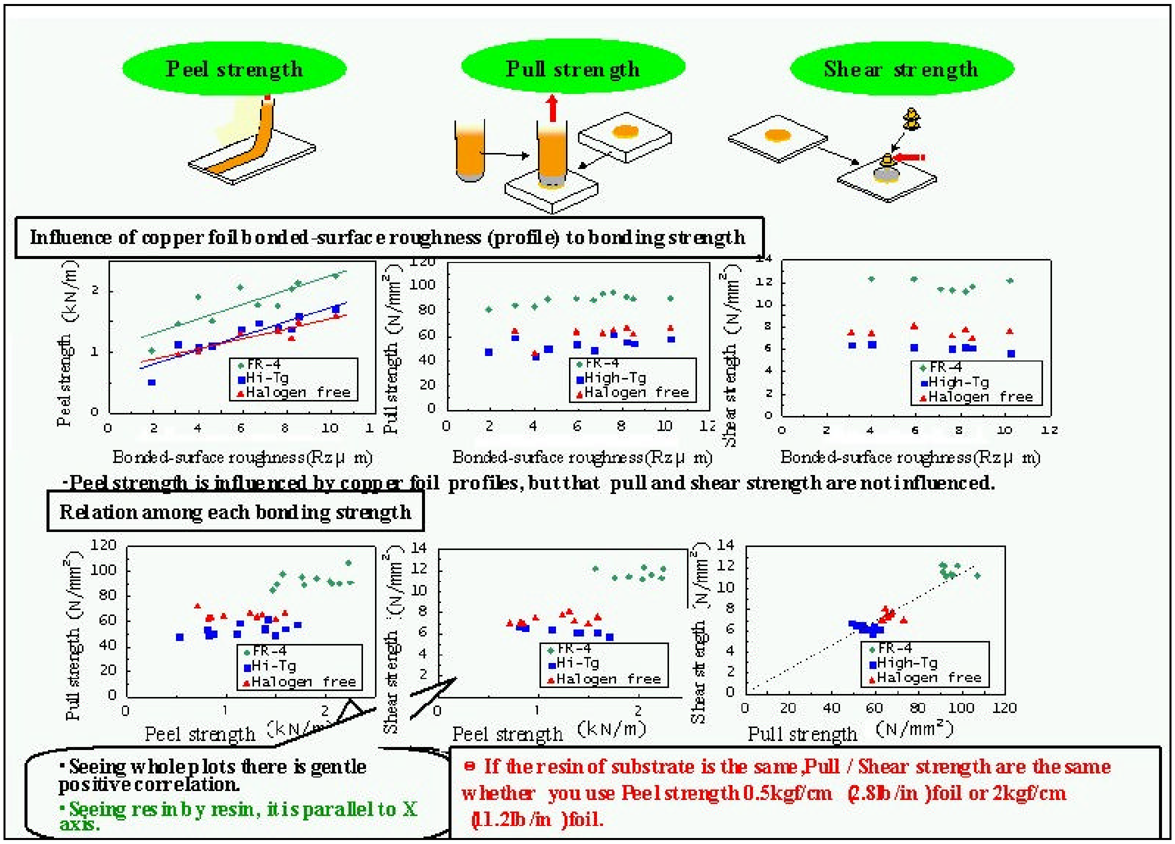


Figure 8 – Comparison of Bonding Strength Evaluation Methods

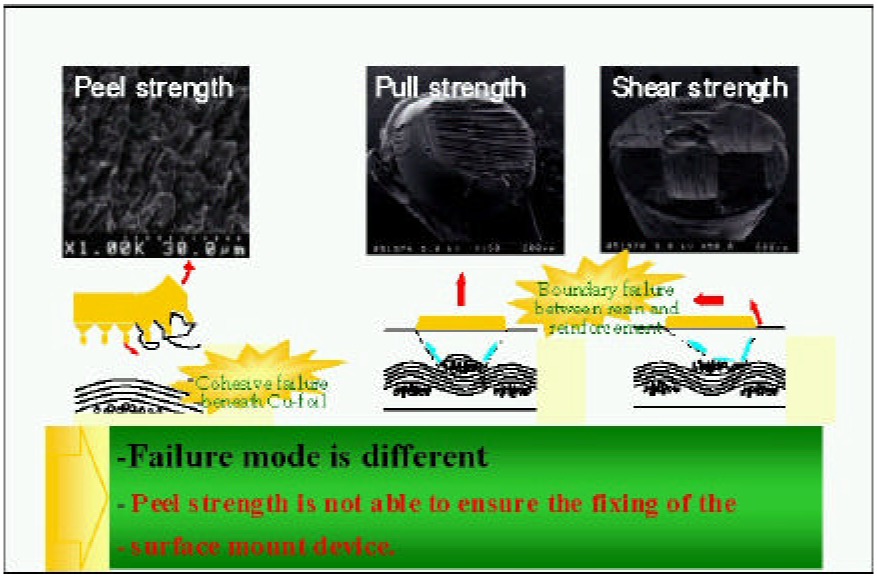


Figure 9 – Observation of Bonding Failure Modes at each Pull/Shear Strength

The reasons are as follows:
(1) When peel strength is measured, bonding is broken inside the layer of resin near the boundary between copper foil and resin.
(2) When pull strength and shear strength is measured, however, bonding is broken deep inside resin near the boundary between resin and glass cloth (see Figure 9).

Surface-mount boards are believed to require pull or shear strength rather than peel strength. This indicates that if the chemical adhesion between resin and copper foil is sufficient with "cohesive failure mode", using high-profile copper foil for attaining even higher peel strength does not prove to be effective in increasing the reliability of component mounting. Instead, it will only be a hindrance to maintaining and ensuring signal quality for high-frequency circuits.

Copper Foil for High-Frequency Substrates

Various types of copper foil are manufactured by different methods and under different conditions. Figure 10 shows the grain structures, surfaces, and physical properties of three kinds of our copper foil products: (1) III (HTE), (2) Super-HTE, and (3) VLP.

Our III foil is used for general purposes and has a columnar grain structure. Our Super-HTE foil recrystallizes when heated during lamination-press and exhibits a large grain structure afterward. The foil therefore demonstrates a high degree of elongation during and after heating (lamination-press). It is used for inner layers of high multilayer boards or for flexible printed wiring boards. Our VLP foil consists of stacked tiny crystals. The foil is therefore characterized by high tensile strength and a very low surface (mat side) profile. Because of its very low profile, the foil is used for IC package substrate and other applications requiring fine circuit patterns. The foil is also used for TAB (Tape Automated Bonding) applications because it has high tensile strength (rigidity) property.

For high-frequency applications (the subject of this paper), low-profile copper foil is desirable in that it keeps transmission loss small. Therefore our VLP copper foil is recommended. To improve our VLP foil's adhesion to high-frequency substrate resin, we treated the above-mentioned additional "Micro nodule" on to the bonding-surface of VLP copper foil. This product is named "MQ-VLP" (see Figure 11), which we have been promoting for high-frequency substrates application.

Looking from the requirement to maintain and ensure signal quality in high-frequency substrates, we believe that the necessity for low-profile copper foil will increase accordingly.

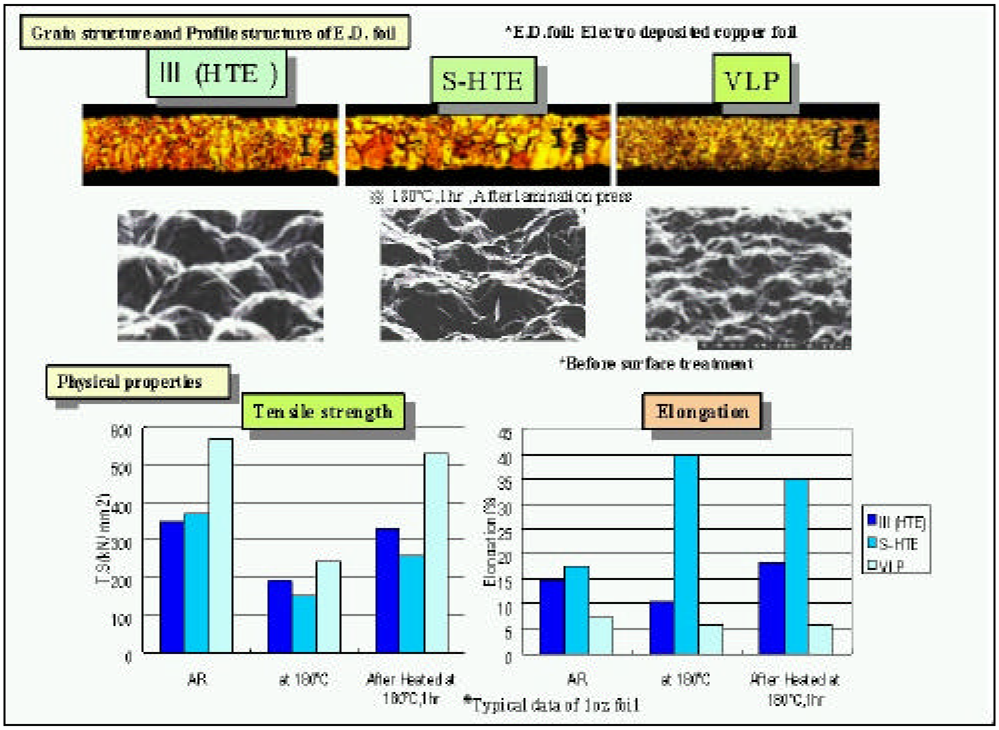


Figure 10 – Grain Structure Profile Structure, and Physical Property of Copper Foil

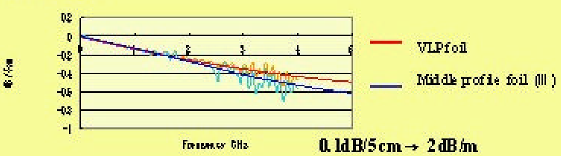
Application

- High-frequency (Low Df/Dk)PWB

Features

- Low signal attenuation
  → Low signal attenuation due to very low profile copper foil
- Good adhesion to Low Df/Dk resin
  → Good adhesion to Low Df/Dk resin is obtained by the effect of " Micro nodule".

<MQ-VLP>



- Approximately 2dB/m (at 5GHz) lower signal attenuation compare with middle profile copper foil.

- "Micro nodule" works for improvement of Low Df/Dk resin adhesion.
  → MQ-VLP achieve sufficient peel strength.

Test Term		MQ-VLP 12μm	MQ-VLP 18μm	MQ-VLP 35μm
Roughness (μm)	Shiny-side Ra	0.25		
	Matte-side Rz	3.8	4.0	4.8
Tensile Strength (N/mm2)	As received	490		
Elongetion(%)	As received	5.0	7.0	10.0
Peel Strength (kN/m)	Normal FR-4	1.19	1.3	1.67
	Low Df Prepreg	0.71	0.89	0.98

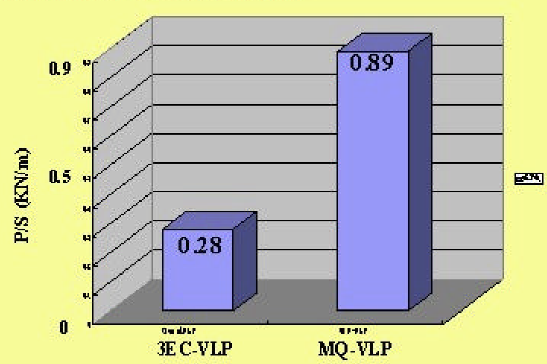


Figure 11 – Copper Foil for High-Frequency Board MQ-VLP