Copper Foil Technology for High-Frequency Applications

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Copper Foil Division

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Copper Foil Technology for High-Frequency Application

1.Transmission loss

2. Conductor loss

 ?Skin effect

 ?Influence of Copper foil type to conductor loss

3.Dielectric loss

 ?Nature of Low-Df/Dk resin and its influence to adhesion

 ?Improvement of bonding strength to the Low-Df/Dk resin

4.Review of Bonding strength

5.Copper Foil for High-Frequency substrates

Transmission loss

Breakdown of Transmission loss

Transmission loss (a)= Conductor loss(a $_c$)+ Dielectric loss(a $_d$) + Radiation loss(a $_r$

Conductor loss(**a** $_c$) : $a_c = \frac{Rs}{2Z_0}$ $\qquad Rs = \frac{1}{ds} = v\overline{p\ f\mu_0 ?}$

Rs: Skin resistance, Z_0:Characteristic impedance, f: Frequency,
μ_0: Space permeability, ? : Conductor resistance

Dielectric loss(**a** $_d$) : $a_d = \frac{p}{?\ g}\text{tand}$

$= Kfv\overline{e_r}\ \text{tand}$

$? = \frac{V}{f}$, $V = \frac{C}{v\overline{e_r}}$

? p /C? K

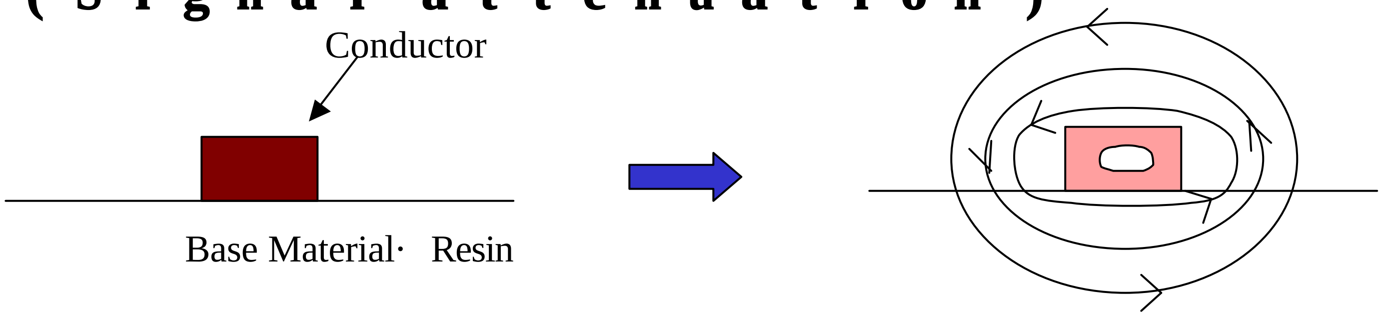
? g: Wavelength in the conductor, V:Signal velocity, C: Velocity of light,
e r: Dielectric constant, tand :Dielectric dissipation factor

Radiation loss(**a** $_r$) : Influenced by circuit design.

? At High-frequency range, Conductor loss increase by increment of Skin resistance.

Conductor loss

(S i g n a l a t t e n u a t i o n)



Skin Effect

When alternating current passes conductor, the magnetic flux changes. So the counter electromotive force generates and current will be difficult to pass.This phenomenon is remarkable as frequency become higher. And current will pass almost only surface, so the high frequency resistance will increase.

$$Rs = \frac{1}{d \cdot s} = \sqrt{\frac{p\ ?f?\mu_0}{s}}$$

Skin Depth

Thickness of skin part where current passes.

$$= \sqrt{p\ ?f?\mu_0 \cdot\ ?}$$

f :Frequency， μ_0:Space Permeability，
? :Conductor Resistance
Rs:Skin Resistance， d:Skin Depth

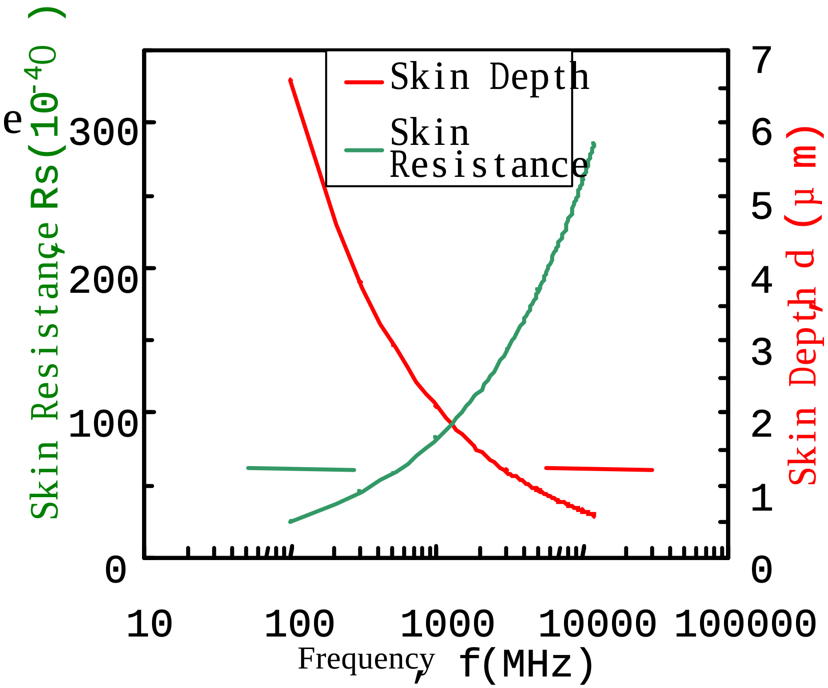
Skin Resistance

Because of skin effect, effective area where current passes decrease, so resistance increase.

? Skin Depth is thin in inverse proportion to square root of frequency.

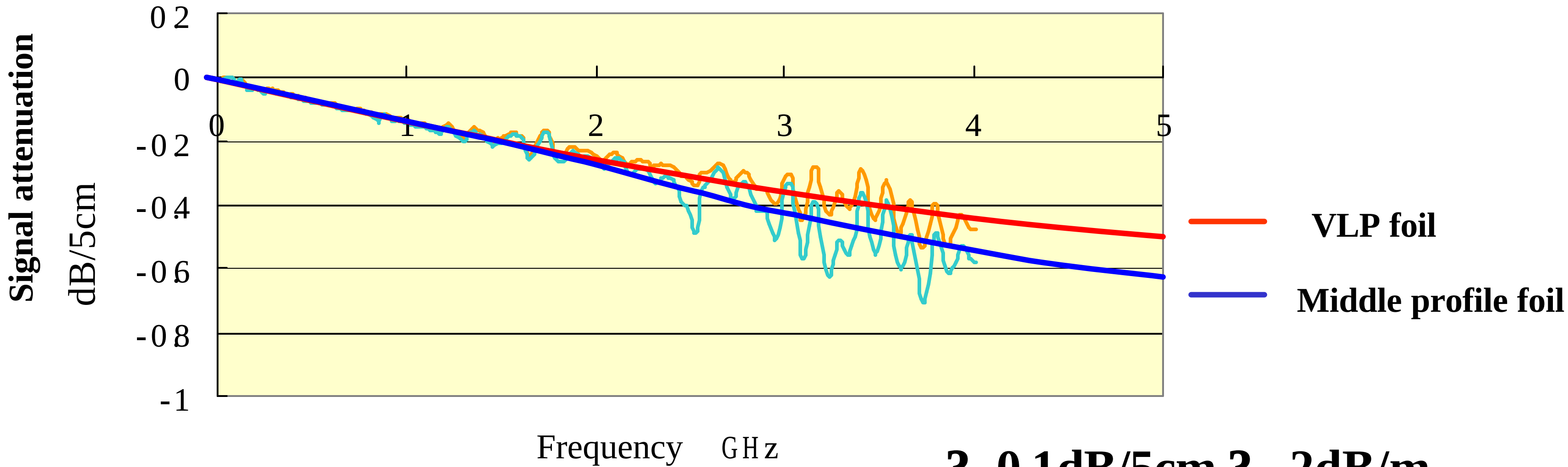
Skin Effect

Frequency	Skin Depth (μm)	Skin Resistance (10^{-4} Ω)
100 MHz	6.61	26.1
300 ?	3.82	45.2
500 ?	2.96	58.3
1 GHz	2.06	82.5
3 ?	1.21	142.9
5 ?	0.93	184.5
10 ?	0.66	260.9
12 ?	0.60	285.8



The surface shapes of conductor will influence the resistance as signal frequency becomes in the range of GHz.

Influence of copper foil type to conductor loss



? 0.1dB/5cm ? 2dB/m

Transmission loss varies depending on the type of copper foil used for a conductive trace.

Signal trace made by VLP foil show lower signal attenuation than that of middle profile foil.
? 2dB/m of signal attenuation difference at 5GHz.

Influence of copper foil type to conductor loss

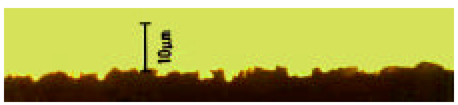
Profile of the copper foil

Rz=10.5µ m

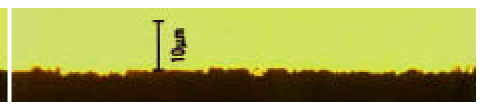
Rz=6.8µ m

Rz=4.8µ m

Rz=3.8µ m



Rz=2.9µ m



Foil Profile depending on Foil Type and Thickness

	70µ	35µ	18µ	12µ
? (HTE)	10.5	7.0	5.0	4.5
S- HTE	10.5	7.0	5.0	4.5
VLP	6.8	4.8	3.8	3.2

? Typical Data

S : Standard >Rz 10.2µ m

L : Low Profile < Rz10.2µ m

V : Very Low Profile < Rz 5.1µ m

? IPC4562 3.4.5

In the High-Frequency range, propagation distance of middle/high profile foil become longer due to skin effect.

It may / will cause problems such as signal attenuation and signal delay.

Conductor loss evaluation by Q factor

Confirmation of relation between copper foil bonded-surface roughness (profile) and conductor loss

・ Circuits (resonance circuits) using copper foil with several different levels of bonded-surface roughness (profiles) have been prepared for the measurement.

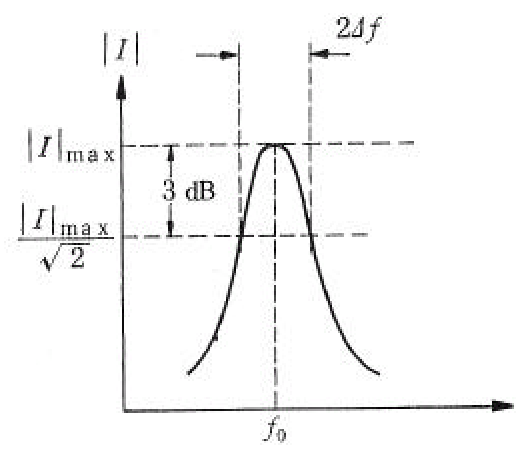
Q factor： The value is indicated by $f_0/2?f$, at the resonance circuit consists of Inductance (L) and Capacitance (C).
The ? f is a frequency difference between resonance frequency (f_0) and the frequency of the point at 3dB lower current from maximum resonance current.
*The circuits having higher Q factor, show lower transmission loss

$$a = \frac{p}{? g \cdot Q}$$

a ： Transmission loss

Q： Q factor

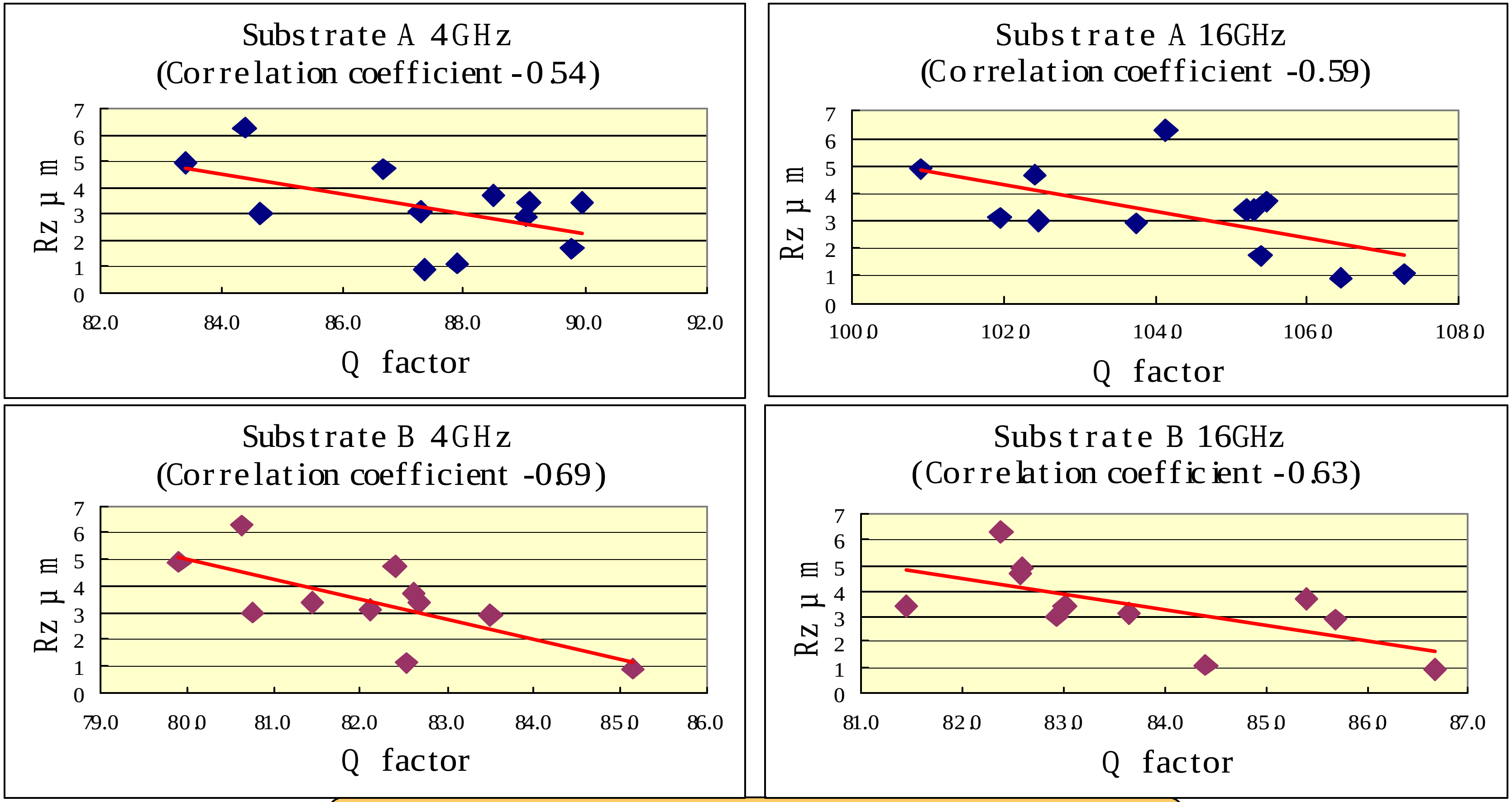
? $_g$:wavelength



resonance characteristic

Relation between copper foil bonded-surface roughness (profile) and Q factor

Bonded-surface roughness and Q factor



Lower Rz (profile) show higher Q factor

? Low-profile copper foil is more effective in keeping transmission loss small.

Conductor loss

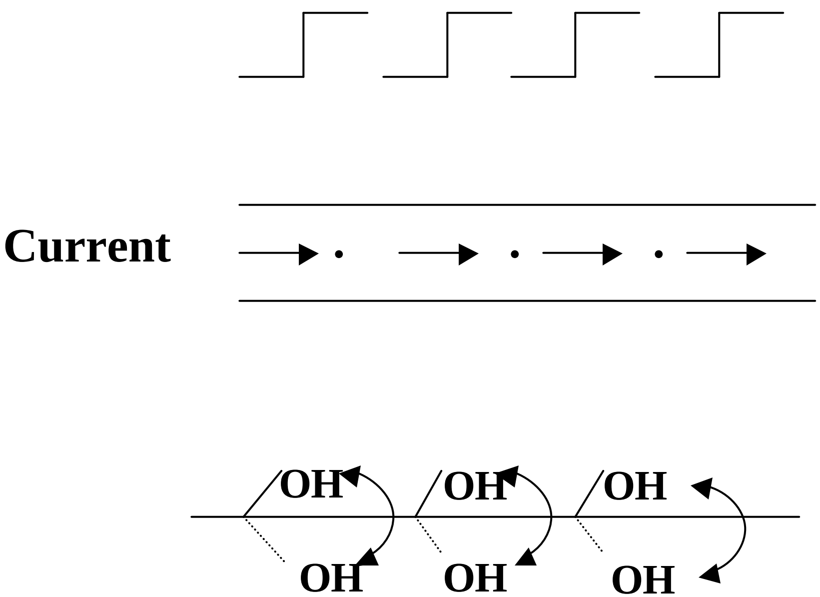
- Skin resistance becomes greater with increasing signal frequency, which
  causes increase in conductor loss.
- In the High-Frequency (GHz) range, transmission loss varies depending on the type of copper foil used for a conductive trace.
  - -Low profile copper foil is more effective in keeping transmission 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.

- **Low profile copper foil are expected to become more indispensable for ensuring the transmittal of signal a frequencies of 1GHz or higher.**

Dielectric loss

Dielectric loss

Dielectric loss



$$\alpha_d = Kf\sqrt{\varepsilon_r}\cdot\tan\delta$$

α_d : Dielectric loss

K : Constant

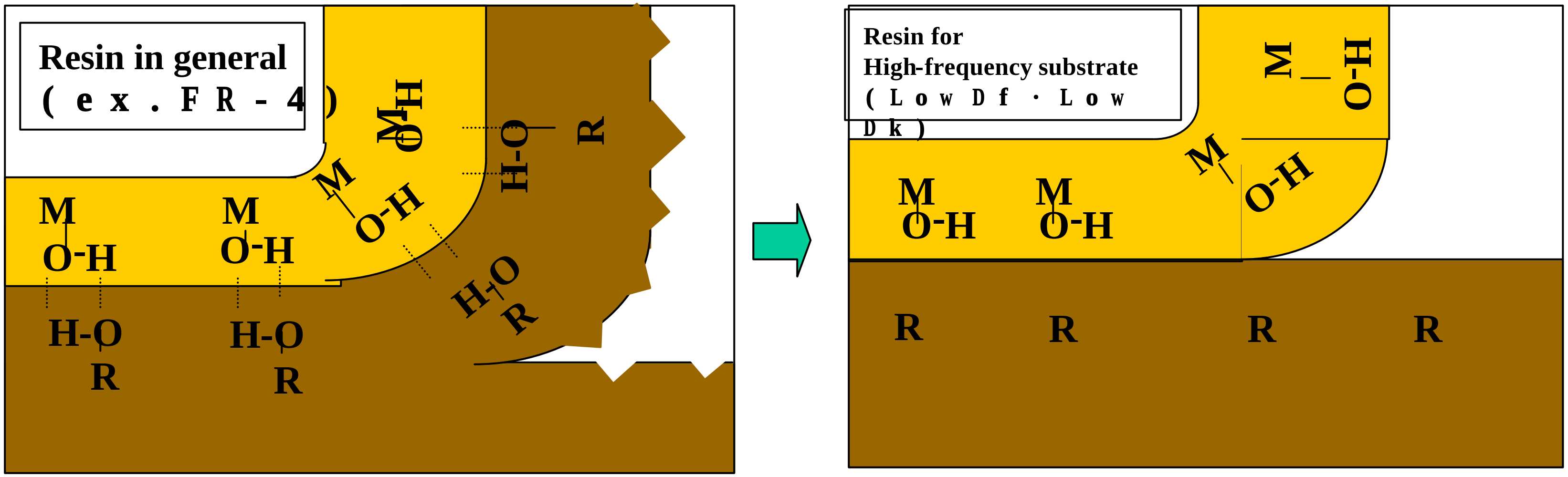
F : Frequency

ε_r : Dielectric constant(Dk)

$\tan\delta$: Dielectric dissipation factor(Df)

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 (the angle of the lag in electric displacement). In such a situation molecular friction generates inside resin, creating heat, which results in transmission loss.

Adhesion between copper foil and resin for High-frequency substrate



・ Resins used for high-frequency substrates contain fewer (or in fact no) substituents with high polarity so that electric field changes does not cause polarization easily.

? It reduce chemical adhesion to copper foil.

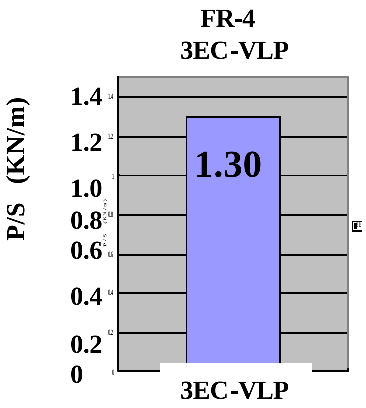
・ The mode of bonding failure change to boundary failure from cohesive failure.

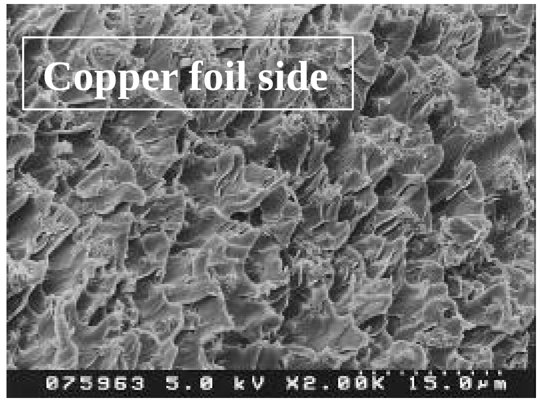
? That is why high-frequency substrates show lower peel strength.

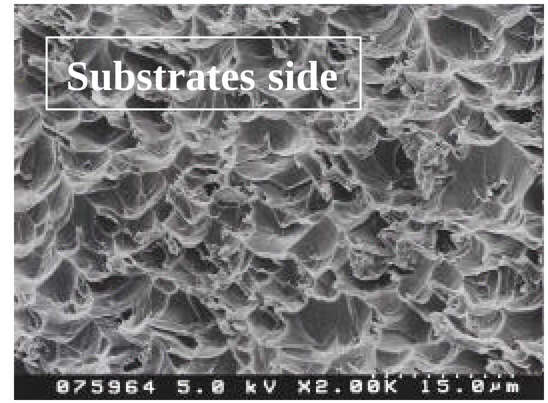
Peel strength comparison FR-4 substrate and High-frequency substrate

FR-4

Cohesive failure (Bonding is broken inside resin.) ? High Peel strength

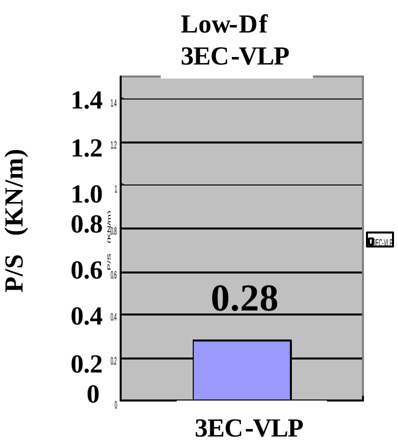


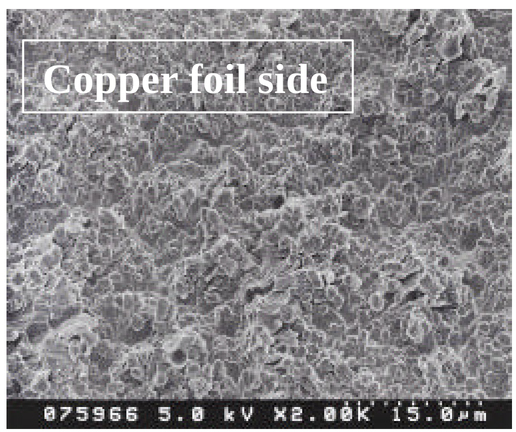


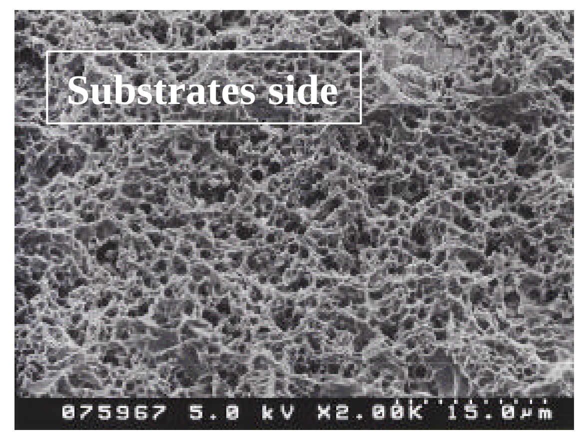


Low Df substrate

Boundary failure (Bonding is broken at the boundary of copper foil and resin.)







- **The Low Df substrate has boundary failure, because of its poor chemical adhesion to copper foil.**

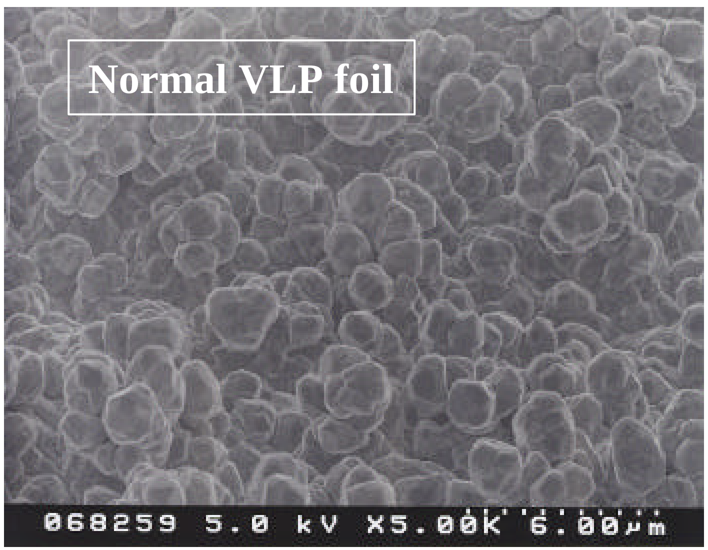
Improvement of bonding strength to the High-frequency substrate

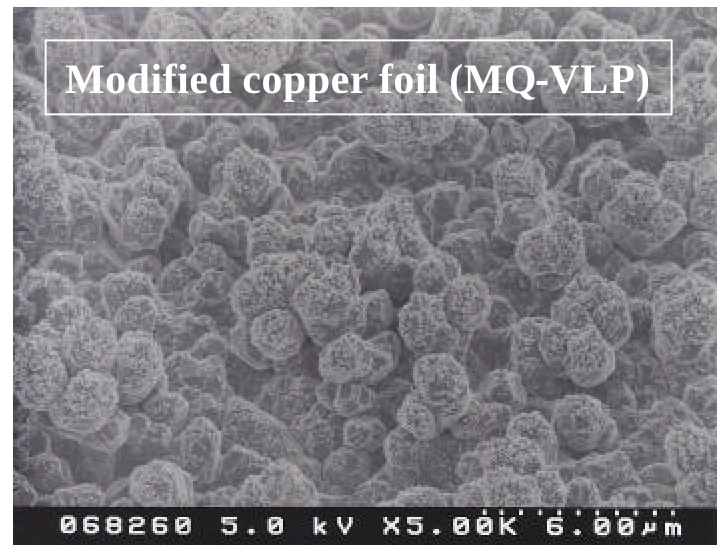
Improvement of bonding strength to the High-Frequency substrate

? The peel strength must be improved without compromising the high-frequency property of conductive trace (with bonded surface profiles kept low).

Improvement Action

The “Micro nodule” increased copper foil’s surface area without changing its profiles, and made it easier for resin to stick firmly.





Provide minute copper particles (Micro nodule)

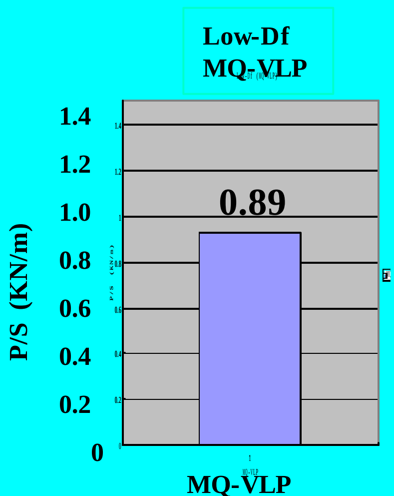
Color pattern

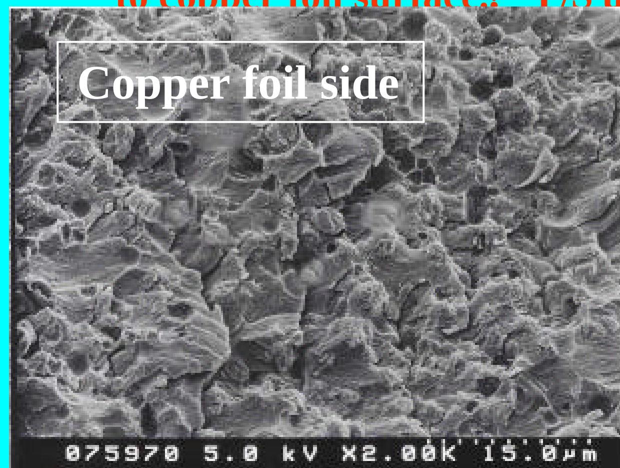
Color pattern

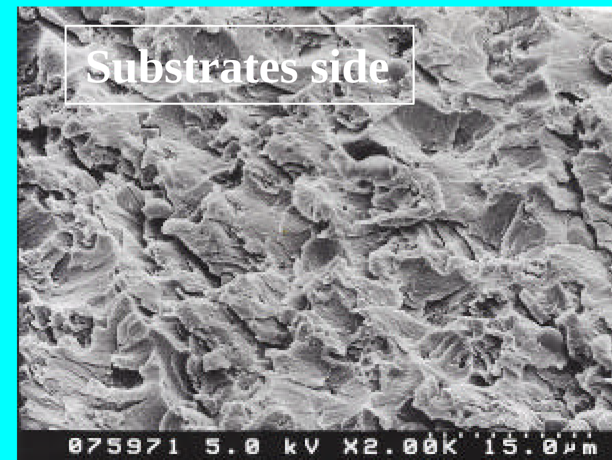
Improvement of bonding strength to the High-frequency substrate

Modified foil : MQ-VLP

The mode of bonding failure is changed to cohesive failure from boundary failure by addition of minute copper "Micro nodule" to copper foil surface.? P/S up



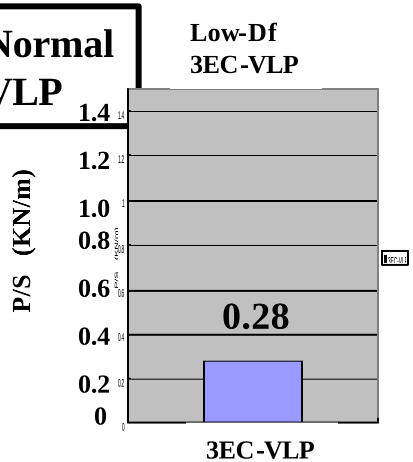


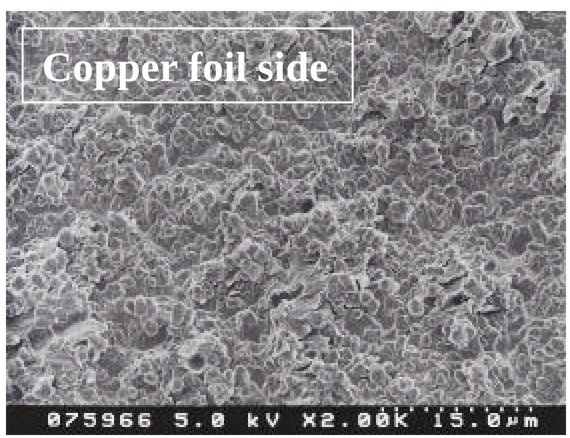


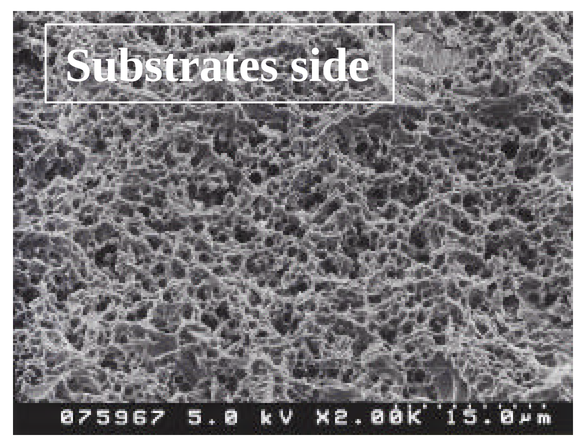
Cohesive failure

Comparison

Normal VLP





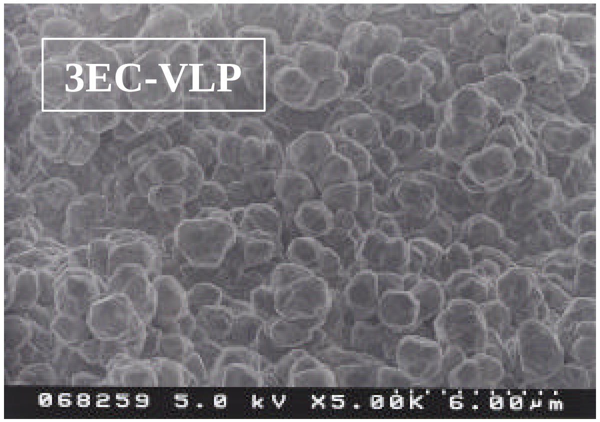


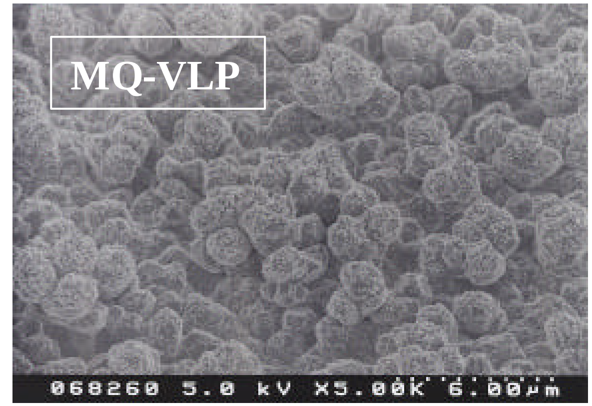
Boundary failure

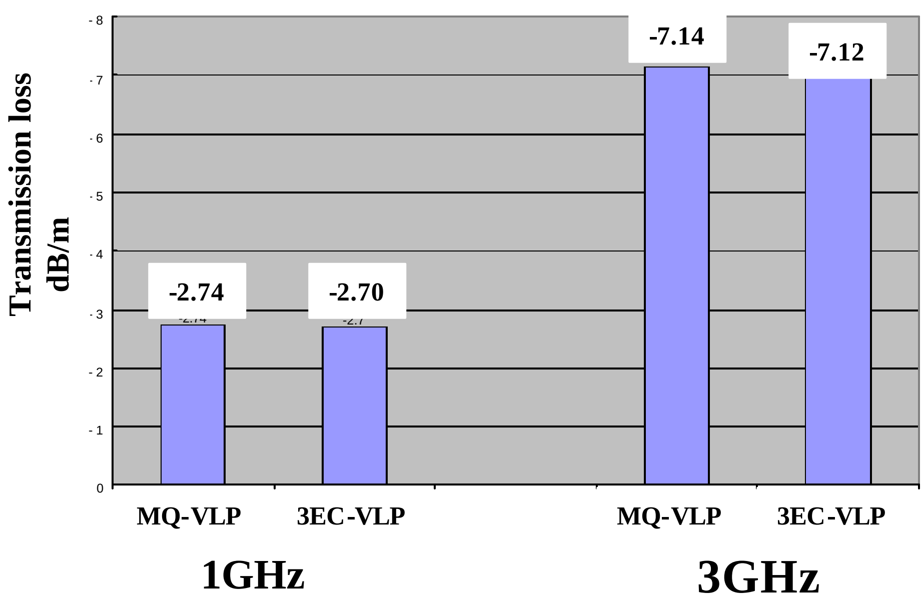
Influence of Micro nodule to transmission loss

Conformation

Conformation of influence to transmission loss by “Micro nodule” treatment





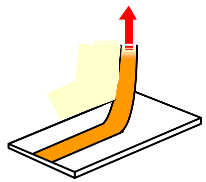


? Difference in transmission loss is not observed.

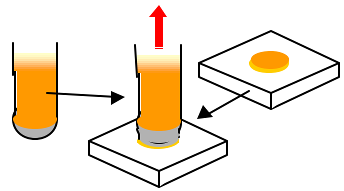
Review of
Bonding Strength

Comparison of bonding strength evaluation methods

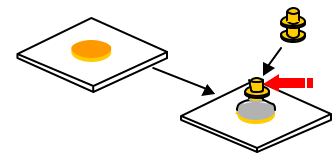
Peel strength



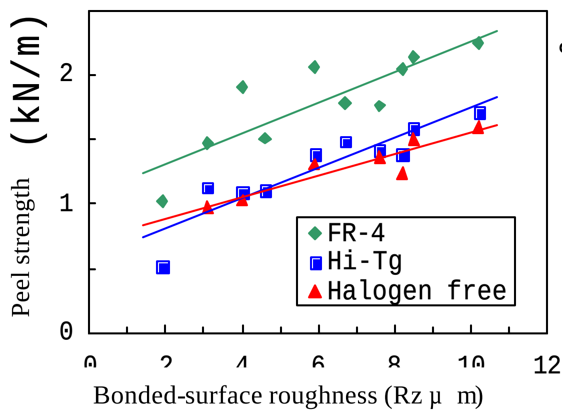
Pull strength

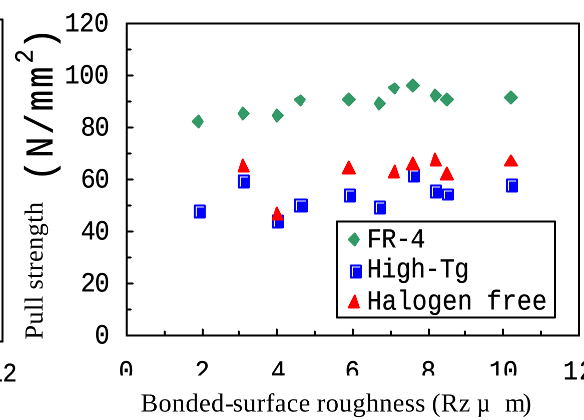


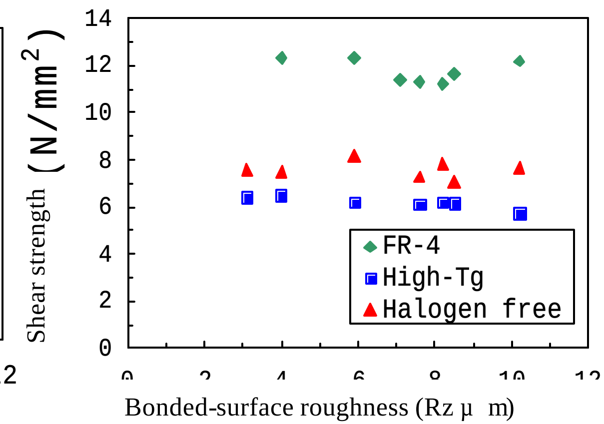
Shear strength



Influence of copper foil bonded-surface roughness (profile) to bonding strength



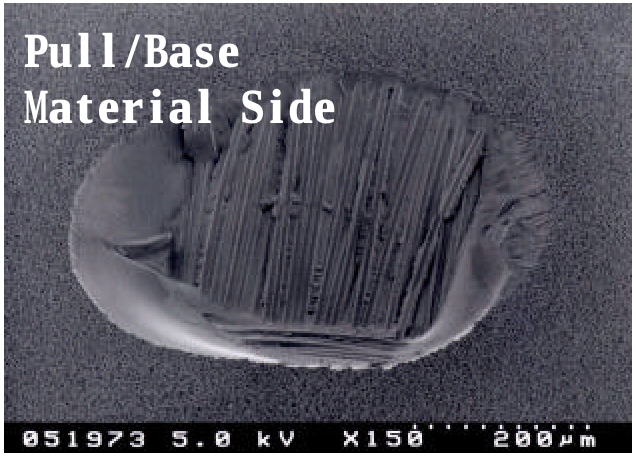


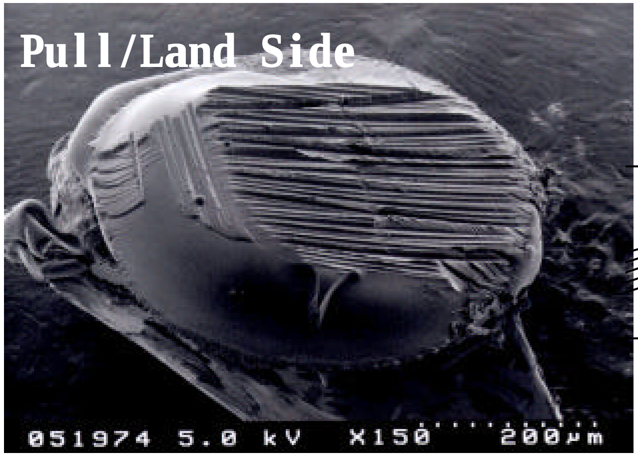


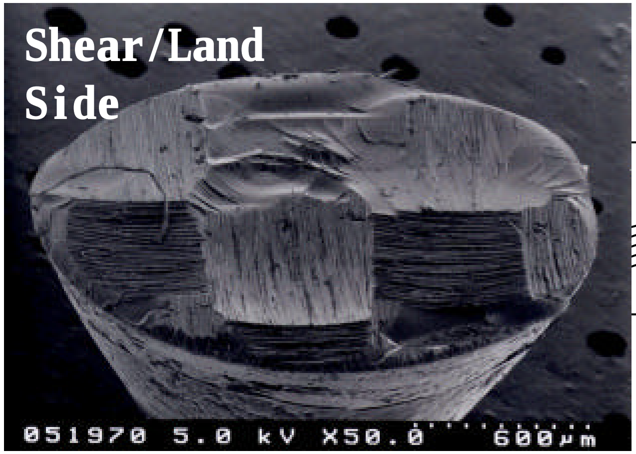
- **Peel strength is influenced by copper foil profiles, but that pull and shear strength are not influenced.**

Failure mode observation of Pull & Shear strength

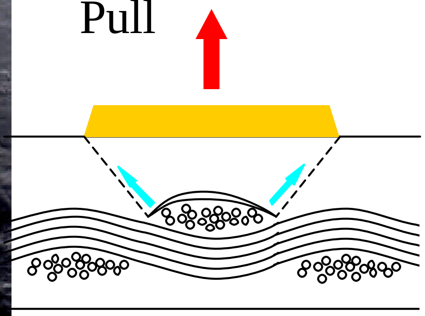
Pull/Shear Strength

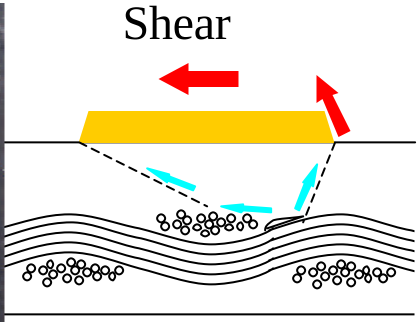






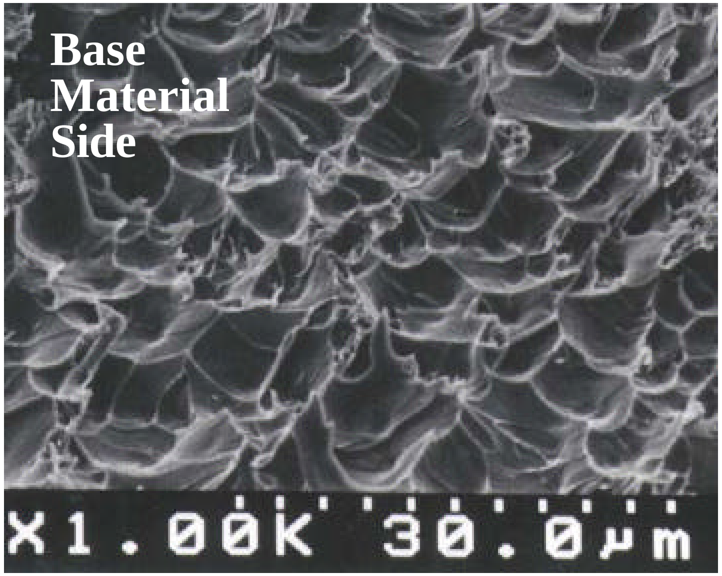
Typical Picture

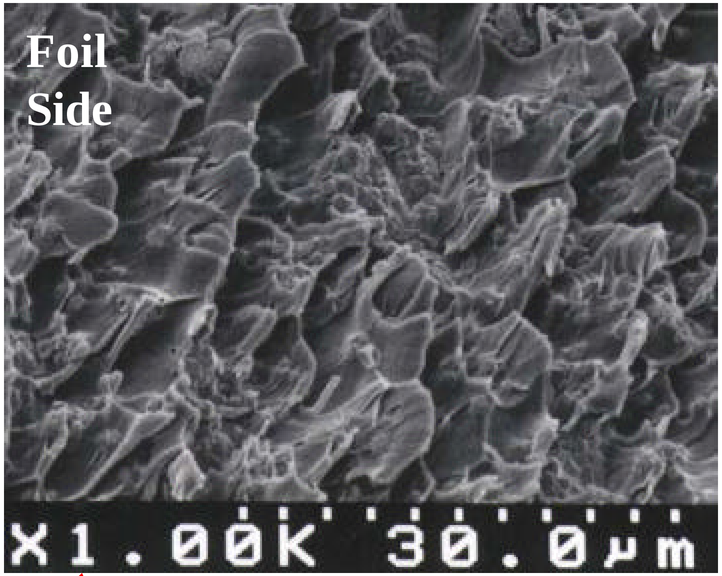


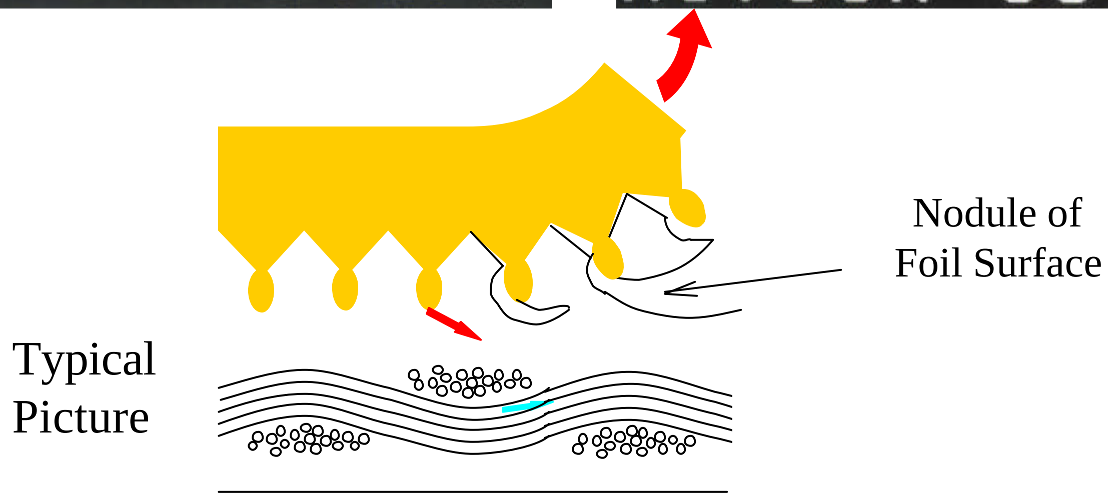


Failure mode observation of Peel strength

Peel Strength

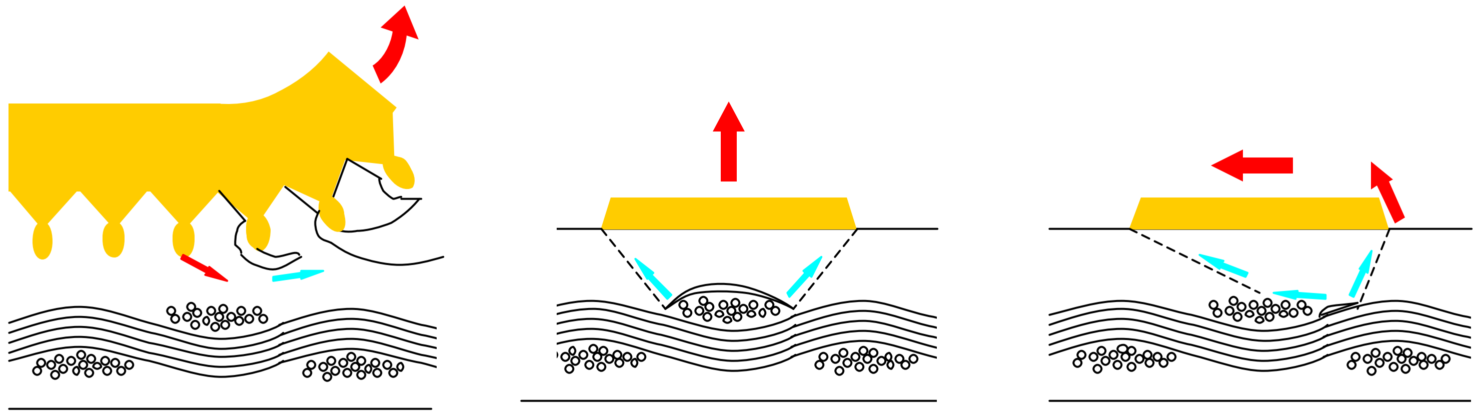






Failure mode comparison

Difference of Failure Mode due to Evaluation Method of Bonding Strength



Peel Strength　　Pull Strength　　Shear Strength

Resin is cracked by anchor nodule of Cu foil surface.

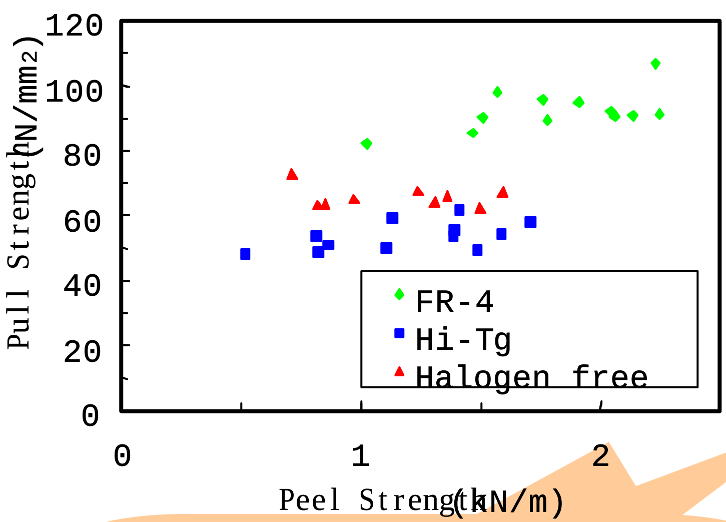
Boundary between resin and glass-cloth originated the failure.

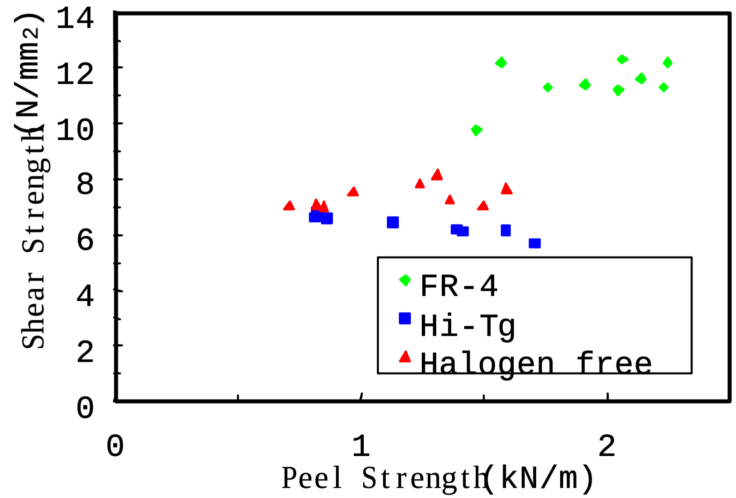
-Failure mode is different

-Peel strength is not able to ensure the fixing reliability

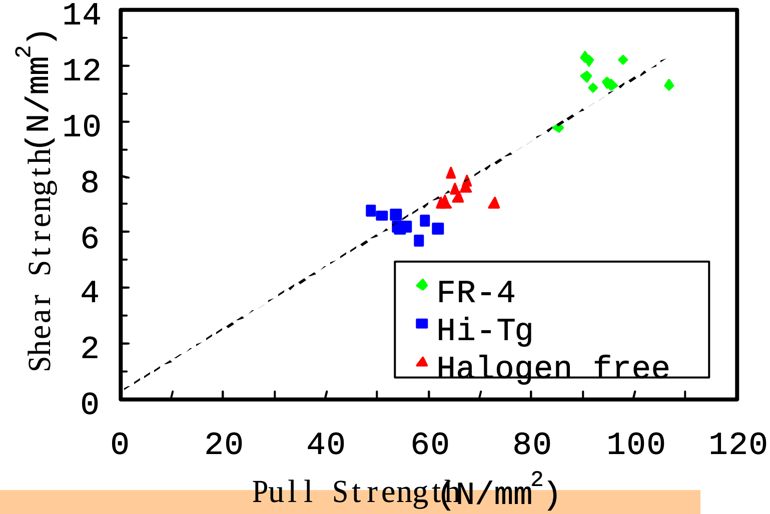
-of the surface mount device.

Relation among each bonding strength





- Seeing whole plots there is gentle positive correlation
- Seeing resin by resin ,it is parallel to X axis.



- Plots are collected for each kind of resin.
- Strong positive correlation

? If the base material is the same, Pull/Shear Strength is the same either you use Peel Strength 0.5kgf/cm（ 2.8lb/in） foil or 2kgf/cm（ 11.2lb/in） foil.

Bonding strength

-Failure mode of Peel stren
from that of pull /shear str

?Peel strength is not able to ensure
the the surface mount device.

-Even 2.0 Kgf/cm P / S copper foil show
Pull /Shear strength as 0.5Kgf/cm P /
when the base material is the s

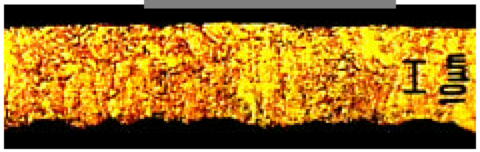
Copper Foil for High-Frequency substrates

Grain structure, profile structure, and physical property of copper foil

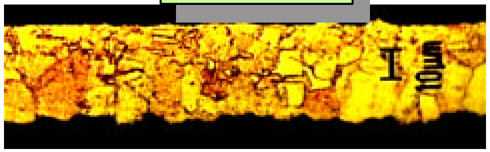
Grain structure and Profile structure of E.D. foil

***E.D.foil: Electro deposited copper foil**

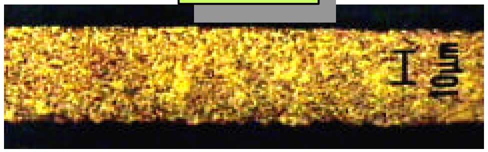
? (HTE)



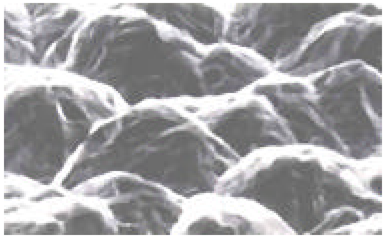
S-HTE

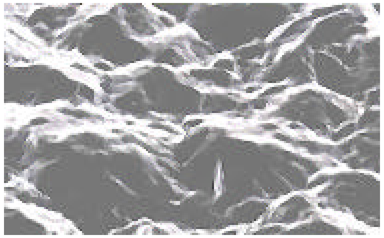


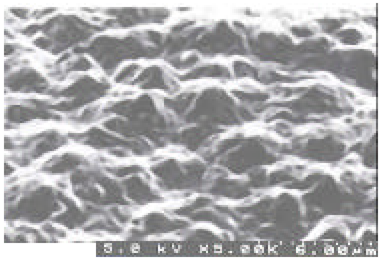
VLP



? 180? ,1hr, After lamination press



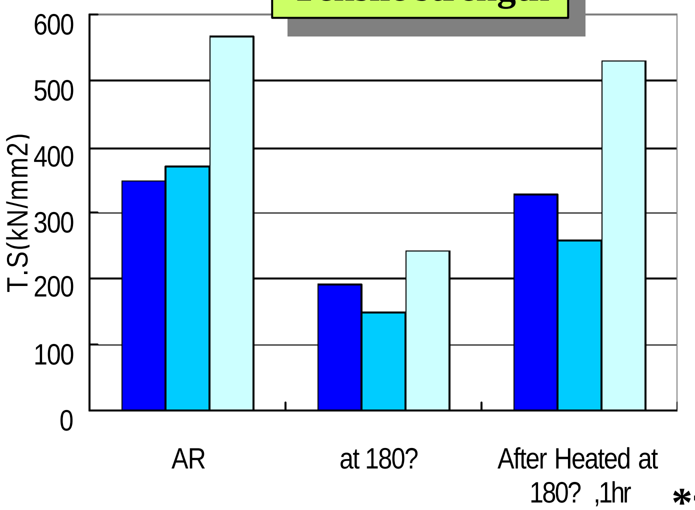




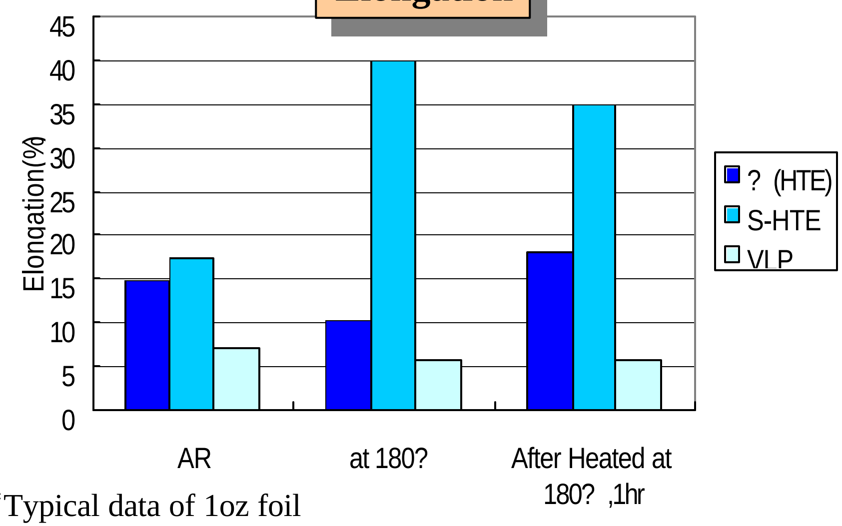
***Before surface treatment**

Physical properties

Tensile strength



Elongation



*Typical data of 1oz foil

Fig.11. Copper foil for High-Frequency board MQ-VLP

Application

- **High-frequency(Low Df/Dk) PWB**

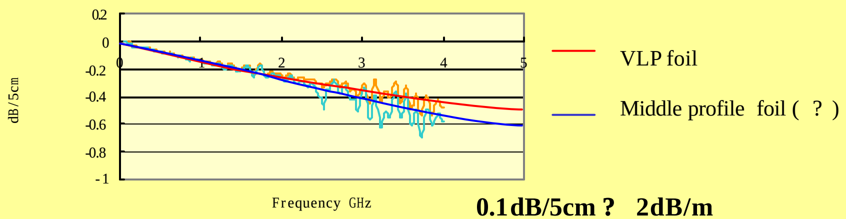
Features

-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".

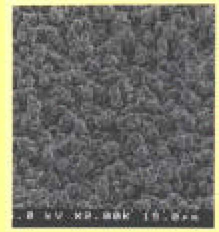


0.1dB/5cm ? 2dB/m

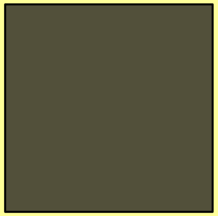
- **Approximately 2dB/m (at 5GHz) lower signal attenuation compare with middle profile copper foil.**

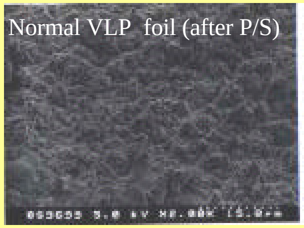
< MQ-VLP>

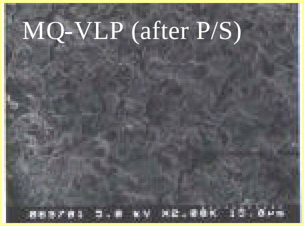
Copper foil matte side



Matte side color







- **"Micro nodule " works for improvement of Low Df/Dk resin adhesion.**

? MQ-VLP achieve sufficient peel strength.

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