# Copper Foil for PCB, Simulation and Study on High-speed Digital Circuits

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**ABSTRACT** Pursuant to a higher transmission speed with an increase of the information amount such as Internet of Things (IoT) or big data, a higher frequency band than the microwave band becomes used. The printed circuit board (PCB) which forms apparatuses/products requires low-loss materials in the high-frequency band. In this article, we describe the manufacturing process and the feature of our electro-deposited copper foil, and also explain, based on an actual case, how to model and utilize the electro-deposited copper foil in a high frequency characteristic simulation which is essential for the design and the development of electronic devices.

## 1. INTRODUCTION

There are growing needs for higher speed and higher frequency of telecommunication equipment essential for optical communication systems or mobile telecommunications using millimeter waveband. In order to meet such needs, manufacturers are developing electronic components and, as an example, a high performance PCB which can have high multi-layers with low-dielectric constant and low-dielectric loss tangent is being developed by material manufacturers. The PCB made of polyphenylene ether (PPE)-type resin has less than 1/10 of dielectric loss tangent compared to the conventional one made of glass epoxy-type material, and can have multi-layers which have been difficult with polytetrafluoroethylene (PTFE)-type material which is enhanced in high-frequency properties.

We have been developing and manufacturing an electro-deposited copper foil suitable to PCB for more than 40 years and were involved in making electronic devices operating at higher speed and higher frequency.

In this article, we describe the manufacturing process and the feature of our electro-deposited copper foil, and also explain, using an actual case, how to model and utilize the electro-deposited copper foil in a high frequency characteristic simulation which is essential for the design and development of electronic devices.

## 2. THE MANUFACTURING PROCESS OF THE ELECTRO-DEPOSITED COPPER FOIL

Most of the conductor layers of a PCB are processed to make circuits after an electro-deposited copper foil or a rolled copper foil is press-contacted to a resin based material. In this chapter, we describe the manufacturing process of an electro-deposited copper foil which is especially used at a high ratio.

### 2.1 The Manufacturing Process of the Raw Foil

Figure 1 shows a schematic diagram of the general manufacturing equipment for an electro-deposited copper foil. The electrodes are configured with a drum-type cathode made of titanium or stainless steel and a concentrically opposing insoluble anode such as a noble metal oxide clad electrode or a lead electrode. Copper plating is deposited on the surface of the drum-type cathode by casting copper sulfate electrolyte between both electrodes from the bottom of the equipment and applying electrical current. The drum-type cathode rotates at a predefined rate and the deposited copper plating is continuously peeled off from the surface of the drum-type cathode and then rolled up as a copper foil.

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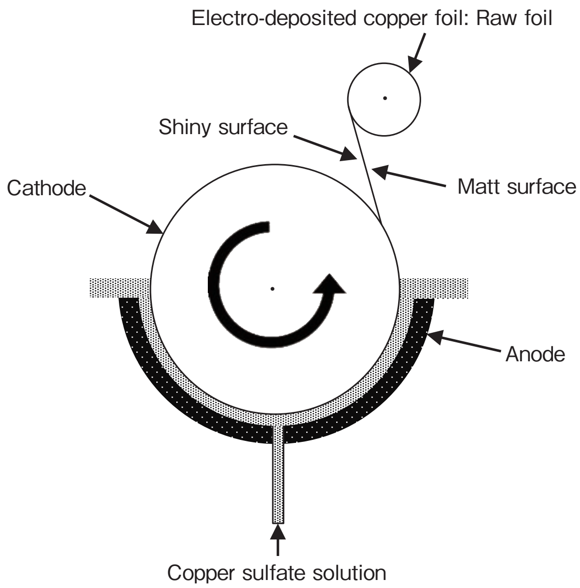


**Figure 1 A schematic X-section of the manufacturing equipment.**

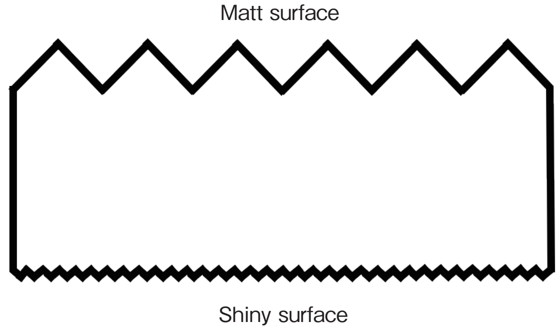


**Figure 2 (a) A schematic X-section of a standard foil.**

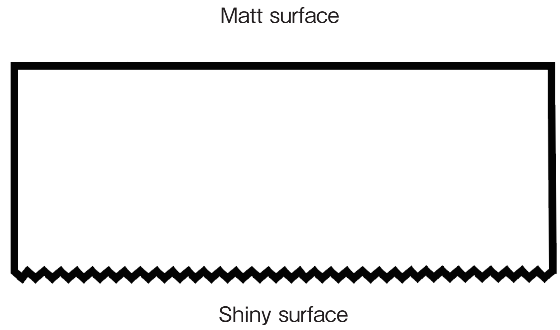


**Figure 2 (b) A schematic X-section of a double side shiny foil.**

The surface of the electro-deposited copper foil which faces the drum-type cathode is called shiny (S) surface. That is because the surface of the drum-type cathode is flat and shining and the copper foil deposited on and then peeled off from the surface of the cathode is also flat and shining. On the other hand, the opposite side of the S-surface is called Matt (M) surface. That is because the M-surface of an early industrial electro-deposited copper foil had basically large asperity and was matt. The thickness of the foil is mainly controlled by adjusting the rotation rate of the drum-type cathode, that is, by adjusting the plating time, therefore the plating time is made shorter by higher rotation rate to make the foil thickness thinner. The 6-210μm of electro-deposited copper foil is currently mass-produced. The handling during manufacturing or using becomes difficult if the thickness is less than 6μm, therefore the foil is required to have its characteristic improved such as a higher strength as described in the followings.

The electro-deposited copper foil has a feature by which its characteristic can be changed by adding various additives into the copper sulfate electrolyte. The M-surface has been keeping its favorable asperity by using organic system additives generally and by using macromolecular organic compound such as animal glue in early stages. The electro-deposited copper foil manufactured with such additive has the cross-section shape shown in Figure 2(a) and is called the standard foil. The manufacturing process in which the M-surface can have flatter and more shinning surface than the S-surface by using several additives is developed afterward. The electro-deposited copper foil manufactured by such process has the cross-section shape shown in Figure 2(b) and been called a double side shiny foil.

### 2.2. The Manufacturing Process of the Surface-treated Foil

Depending of each product, a surface treatment is added onto the raw foil obtained. The electro-deposited copper foil can be categorized as for PCB application and for battery application. Here, we explain a general manufacturing process for the former use.

After cleaning the surface of the raw foil, a roughening particle forming is done as the first process. Specifically the roughening particles which consist of copper particles are formed by plating the surface of the raw foil using a copper sulfate electrolyte with a low copper concentration and a low solution temperature. The roughening particle forming is an important process to obtain adequate adhesiveness with the resin of the PCB by an anchor effect which occurs when the particles dig into the resin of the PCB.

Next, the process to give the foil chemical resistance, heat resistance and/or rust-prevention is done. Describing particularly in the general example, on the roughened side where the roughening particles are formed, that is, on the side where the resin will be adhered, the chemical-resistant and heat-resistant layer which consists of, such as, nickel, zinc and/or cobalt is formed and also rust-preventive layer which mainly consists of chromium for rust-prevention is formed. Last, the silane coupling treatment layer as an adhesion-improving layer is formed. Silane coupling agent is so selected in a manner to be suitable for the resin adherence. The schematic of the copper foil for PCB, which has the surface-treatment construction described above, is shown in Figure 3.

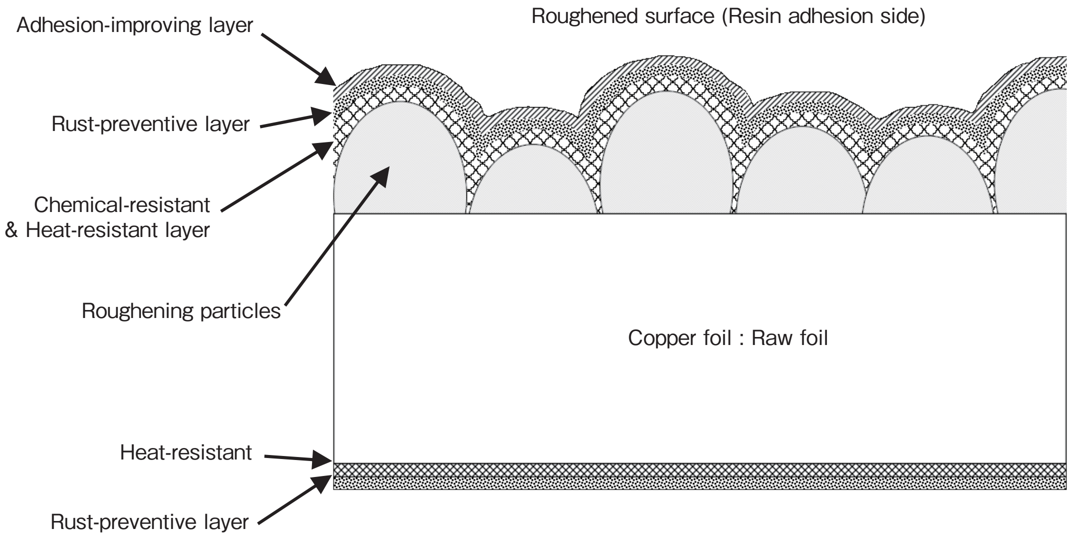


**Figure 3 A schematic X-section of the copper foil for PCB.**

Subsequently, the surface treated foil is cut out into the shapes and sizes, such as sheets or rolls, according to the user's requests and shipped out.

Since the network communications traffic increased recently, a demand of a high frequency PCB for servers, routers and mobile equipment which handles increase in data processing is increasing and enhanced high-frequency characteristics is required for the foil of the PCB, therefore the double side shiny foil which has a roughening particle forming on the M-surface has been developed. The M-surface of the double side shiny foil is a more flat surface than the S-surface and the roughening particles are formed uniformly and finely, therefore the foil meets the requirement at higher frequency characteristic (Figure 4). This type of the copper foil is superior in the circuit linearity (providing the characteristic if the circuit edge is cut linearly with the sight from the direction of the surface after etching) and the etching typified represented as such as an etching factor, therefore the foil meets the requirement of a high-density circuit forming which has an increased demand in recent years.

## 3. FEATURES OF THE ELECTRO-DEPOSIED COPPER FOIL

### 3.1 Crystal Structure

Figure 5 shows X-section crystal structures of the copper foils. The crystal structure of the ordinary state (Figure 5 (a)) shows that the rolled foil is constructed with a layered structure which extends in the rolling direction whereas the standard electro-deposited copper foil shown in Figure 5 (b) is constructed with a pillar structure which extends in the thickness direction of the plate deposited direction. On the other hand, the double side shiny foil, shown in Figure 5 (c), of the electro-deposited copper foil which is manufactured by using special additives is constructed with a random granular structure and its crystal structure has growth and coarsening by a thermal load when it is press-contacted to a resin based material.

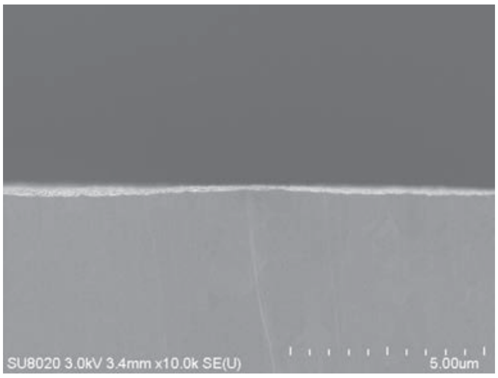


**Figure 4 (a) Matt surface of double side shiny foil: Untreated.**

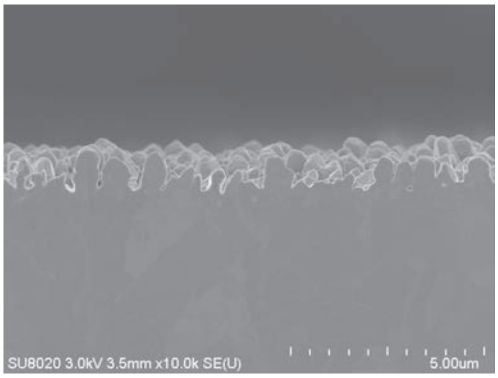


**Figure 4 (b) After treatment.**

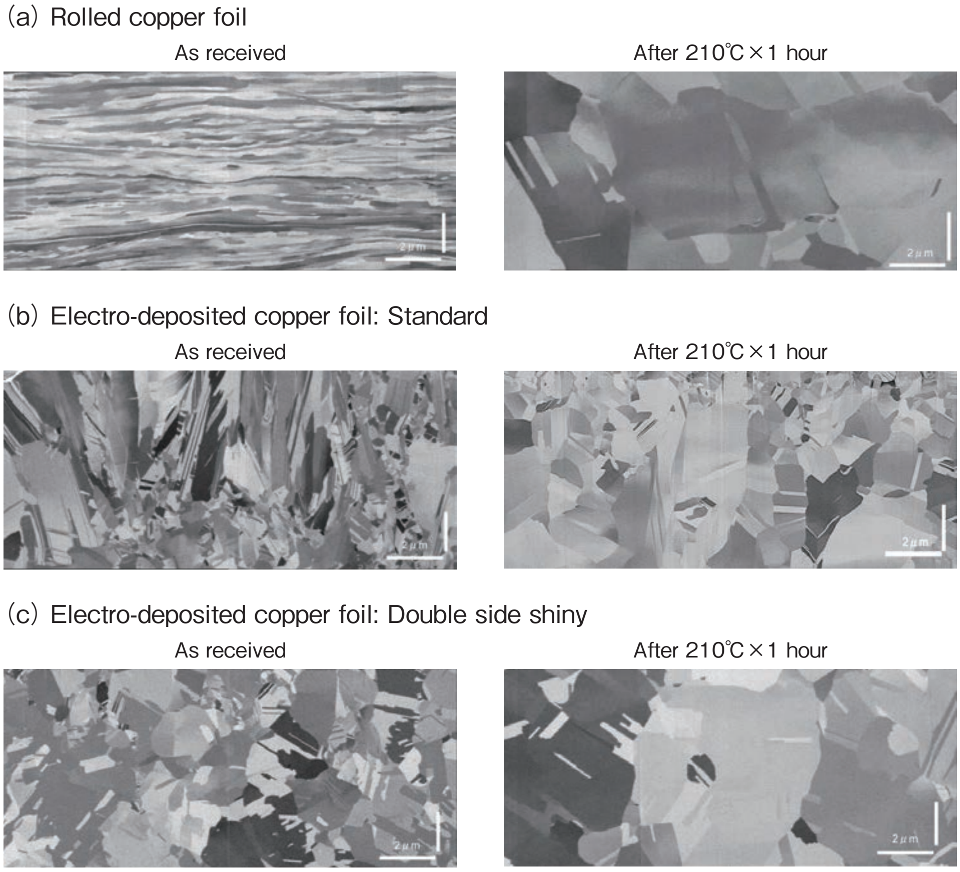


**Figure 5 X-section crystal structures of copper foils.**

### 3.2 Mechanical Characteristics

Except high-strength type used special additives, the electro-deposited copper foil has a tensile strength of nearly 300-400MPa at the ordinary state of both standard foil and double side shiny foil. Since its crystal structure is isotropic, it has small anisotropy of an elongation and its elongation rate is higher because the crystal structure is coarser compared to the rolled copper foil. It also improves its crease performance because its crystal structure becomes coarser by thermal load when it is press-contacted and this characteristic is preferred for a flexible printed circuit.

### 3.3 Introduction of the Typical Products

The variety and characteristics of our typical products of high-frequency compatible electro-deposited copper foil and schematic X-sections of their types are shown in Table 1 and Figure 6. DGTSEU2-MP is called RTF foil which forms roughening particles on the S-surface of the standard foil shown in Figure 2 (a) and classified in Very Low Profile (VLP) as the class of the high-frequency compatible electro-deposited copper foil. F2-WS and FV-WS form roughening particle on the M-surface of the forenamed double side shiny foil and both surfaces including the resist surface are flat, therefore they can be suitable for the application which require enhanced high-frequency properties. The FV-WS is especially classified in H-VLP which is a higher class of VLP and has superior adhesiveness with a resin consisting of a polyphenylene ether (PPE), therefore it is a product proud of its high reliability. FZ-WS is a product developed for the application which requires superior high-frequency properties with maintaining adhesiveness to a resin by a contriving process of the roughening particle forming. Since FZ-WS, FV-WS and F2-WS have, as a base material, a double side shiny foil which is superior in a crease performance, they are preferred for not only a high-frequency substrate but also for the flexible printed circuit board which requires high-frequency performance.

**Table 1 Typical products of high-frequency compatible electro-deposited copper foil.**

| Product/Profile | | FZ-WS/ HVLP2 | FV-WS /HVLP | F2-WS /VLP | DGTSEU2 -MP /VLP(RTF) |
|---|---|---|---|---|---|
| Roughness Rz (at 18 μm) | Resin adhesion side (μm) | 1.1 | 1.2 | 1.8 | 3.0 |
| | Resist Side (μm) | 1.2 | 1.2 | 1.2 | 3.5 |
| Tensile Strength (at 18 μm) | RT (MPa) | 310 | 310 | 310 | 320 |
| | at 180℃ (MPa) | 180 | 180 | 180 | 170 |
| Elongation (at 18 μm) | RT (%) | 9 | 9 | 9 | 12 |
| | at 180℃ (%) | 12 | 12 | 12 | 14 |
| High-Frequency Substrate | | ○ | ○ | ○ | ○ |
| Flexible Printed Circuit | | ○ | ○ | ○ | |
| Semiconductor Package | | | | ○ | ○ |

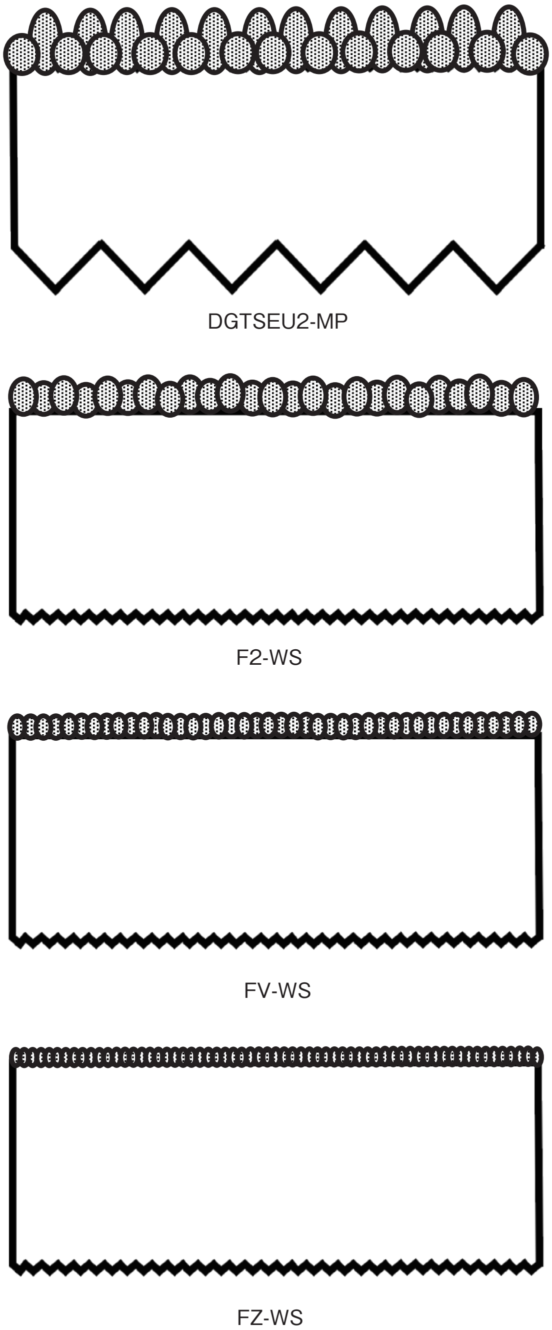


**Figure 6** **Schematic X-sections of high-frequency compatible products.**

## 4. THE EXTRACTION OF THE CONDUCTOR SURFACE ROUGHNESS USING THE S-PARAMETER

As described in Chapter 1, a high frequency characteristic simulation is increasing in its importance in the design and development of the electronic devices and it makes it possible to reduce the number of trial productions and to handle rare events and can significantly improves the quality of the products.

Figure 7 shows the measured attenuation (S21) of the strip-line transmission line generated on the PCB and the result which is calculated with a relative dielectric constant of 3.6 and a dielectric loss tangent of 0.004 for the resin material while the condition of the electric conductivity of the conductor is assumed as infinite. As seen from Figure 7, the difference between the measured value and the calculated value becomes larger as frequency is increasing. This difference is attributed to the determination of the conductor at the simulation therefore the conductor surface roughness and the skin depth which depend on the frequency need to be expressed appropriately. In this chapter, we calculate high-frequency characteristics in consideration of the surface roughness of a conductor model based on the Hemispherical model which quantifies the conductor surface roughness. There are two ways to determine parameters of this conductor model; one way is to determine by observing the surface roughness of the foil with an electron microscope, and the other way is to determine by making a PCB actually and using S-parameter obtained by a vector network analyzer. In this chapter, in consideration of user convenience, we use the latter way to determine parameters of conductor surface roughness model by using the S-parameter.

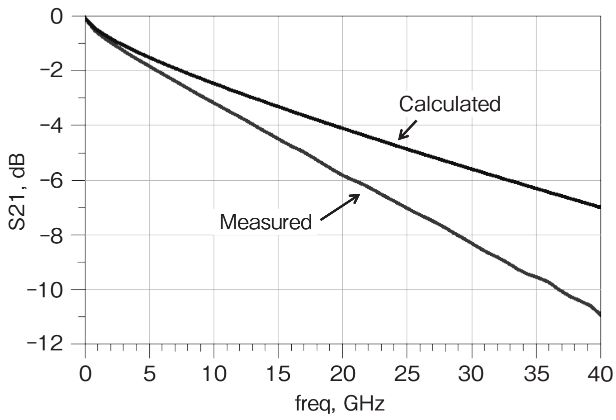


**Figure 7** **Comparison of the calculated and the measured attenuations of the strip-line transmission line.**

Figure 8 shows the X-section of the PCB for S-parameter measurement. Figure 9 shows the S-parameter measurement result of the PCB shown in Figure 8. Using this S-parameter, parameters are determined by fitting to the transmission line model which is compatible with the conductor-surface-roughness. The parameters of our electro-deposited copper foil FV-WS are shown in Table 2. Figure 10 shows the results of the measured value by generating strip-line on the PCB using FV-WS and extracting the parameters, and the calculated value of the simulation. It shows that the measured value and the calculated value of the Hemispherical model simulation are extremely matching.

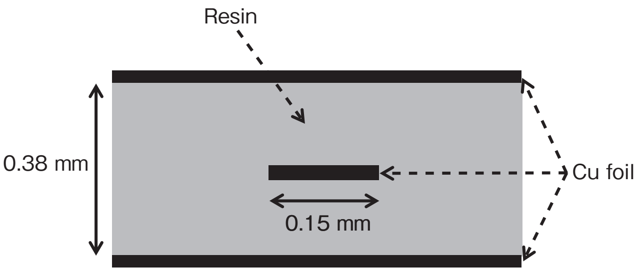


**Figure 8 X-section of the PCB for S-parameter measurement.**

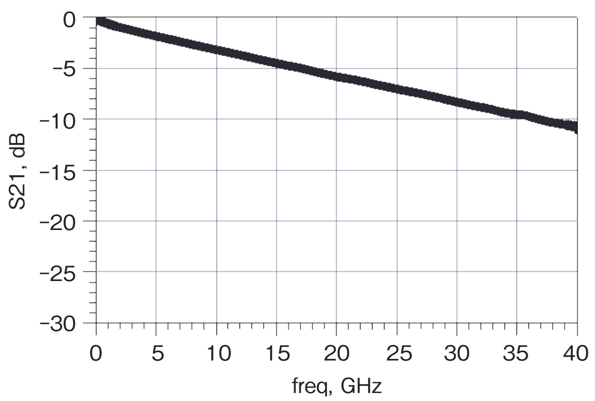


**Figure 9 Measured S-parameter S21.**

**Table 2 Simulation parameters of FV-WS.**

| Parameter | Value (μm) |
|---|---|
| L1Rough | 0.55 |
| L1Bbase, L1Dpeaks | 1.1 |
| L2Rough | 0.36 |
| L2Bbase, L2Dpeaks | 0.72 |

L1Rough : Value of protrusion height (Level1)
L1Bbase, L1Dpeaks : Value of protrusion base width, peak distance between two adjacent protrusions (Level1)
L2Rough : Value of protrusion height (Level2)
L2Bbase, L2Dpeaks : Value of protrusion base width, peak distance between two adjacent protrusions (Level2)

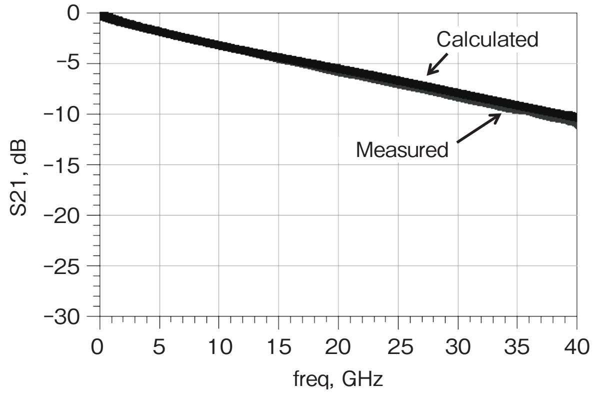


**Figure 10 Comparison of values calculated and measured for the electro-deposited copper foil FV-WS.**

## 5. STUDY OF HIGH-SPEED DIGITAL CIRCUIT

In this chapter, we introduce the transmission characteristics with setting values of the high-speed digital simulation shown in Table 3, using the conductor surface roughness extracted in the previous chapter.

**Table 3 Parameters of high speed digital (HSD) simulation.**

| Parameter | Value |
|---|---|
| Tx, PRBS Bit rate | 28Gbps |
| Tx, PRBS Register length | 7 |
| Tx, AMI Modulation | NRZ |
| Tx, AMI Pre-shoot De-emphasis | 0dB |
| Encoder | No |
| Rx, AMI CTLE | Disable |
| Rx, AMI CDR | Disable |
| Rx, AMI DFE | Disable |

PRBS (Pseudo Random Bit Sequence)
AMI (Algorithmic Modeling Interface)
CTLE (Continuous Time Linear Equalizer)
CDR (Clock Data Recovery)
DFE (Decision Feedback Equalizer)

To see the difference of our electro-deposited copper foils, FZ-WS and F2-WS are added as the comparison objects besides FV-WS described in Chapter 3. Figure 11 shows high-speed digital transmission characteristics at 28Gbps. It shows the eye patterns when the length of the strip-line is changed as 300mm, 400mm and 500mm.

Seeing the eye patterns of 500mm transmission line, the eye pattern of the F2-WS is closed. It is found out that, changing the copper foil of the PCB to FV-WS and FZ-WS, the eye patterns will be improved.

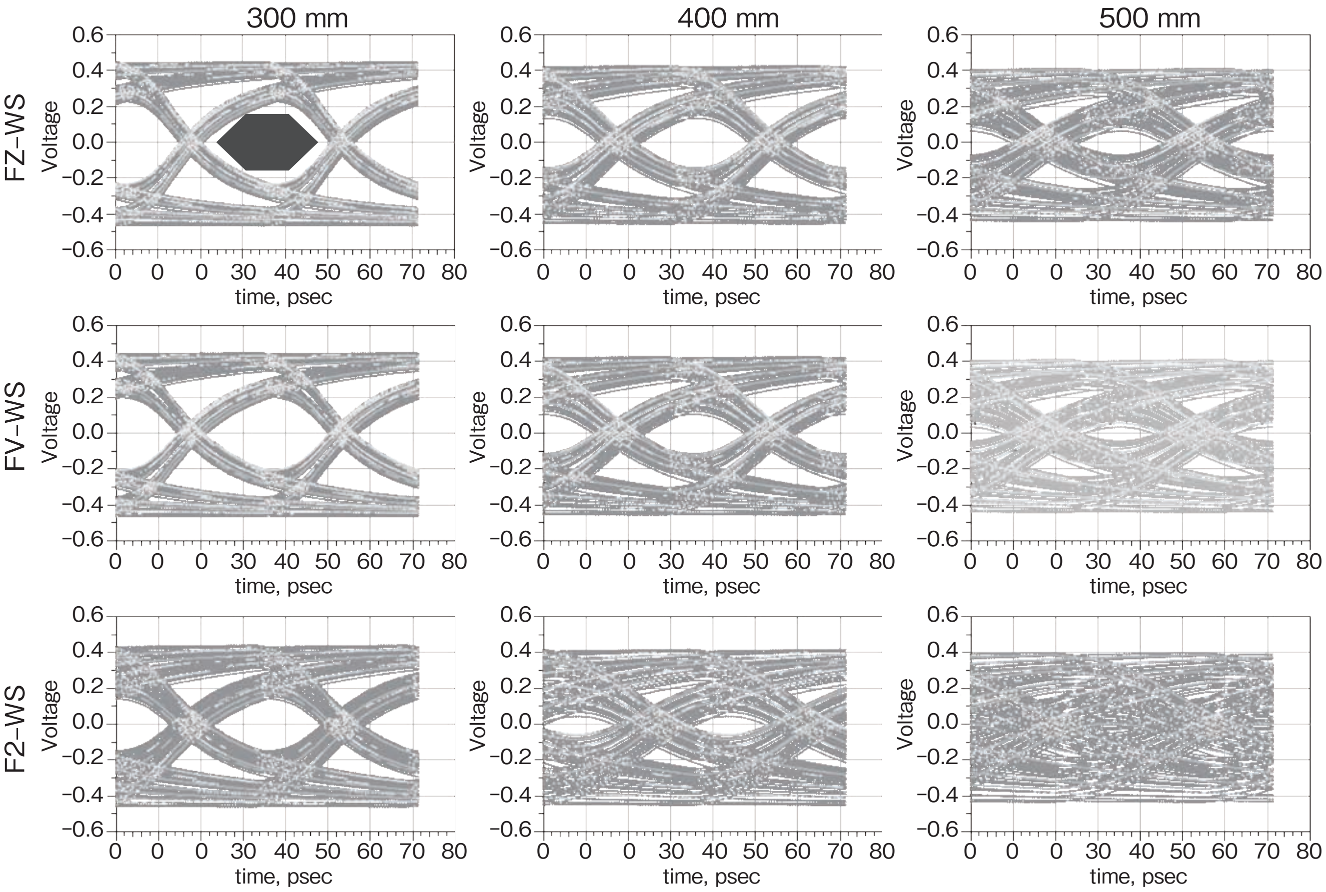


**Figure 11 28 Gbps high-speed digital simulation results.**

The design of PCB which is actually applied for the high-speed digital transmission line is more complicated than this example and has a large influence to high-frequency characteristics. It is assumed that we can contribute to the design and development of high quality high-frequency circuits by establishing high-frequency characteristics of the foil as a conductor which configures the wiring.

## 6. CONCLUSION

The material characteristics of the electro-deposited copper foil for a PCB, which we have been developing and manufacturing, and the example of high-speed digital circuit design by using parameters of conductor surface roughness are explained.

The manufacturing process of the raw foil and the surface processing which is important for the PCB application are explained and crystal structures and mechanical characteristics of our electro-deposited copper foil are explained.

It makes it possible to consider high-frequency characteristics of a copper foil as a conductor comprising PCB, through extraction of the conductor surface roughness parameters by using the S-parameter and using it in a high-speed digital circuit. In order to meet the needs which are becoming more sophisticated in the future, we are going to fuse and improve our electro-deposited copper foil technology and the high-frequency technology and make a contribution to advancement of PCBs and electronic devices which uses those PCBs.

### REFERENCES

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