Fine-Electrode Foil for Particle Physics Experiment

Daisuke Arai,[1] and *Masahiro* Iwamura[1]

Recently, various electronic devices have decreased in size and increased in functionality, as typified by smart phones. In step with this, flexible printed circuit (FPC) boards, which are used as a wiring material in these devices, have been making progress in production techniques, especially, to form finer and denser traces. Using Fujikura's proprietary FPC production techniques, we are working on new products. As an example of these newly developed products, this report describes a fine-electrode foil, which is used in a detector for particle physics experiments.

1. Introduction

Recently, various electronic devices such as smartphones have decreased in size and thickness and increased in functionality with multiple functions integrated in one. One of the necessary parts of these electronics devices is a flexible printed circuit (FPC) of high flexibility and small thickness. In step with the development of these devices, we have met various technical requests such as for the miniaturization and densification of traces [1) 2)].

We are developing new products using fine pitch circuit formation techniques which we have been developed over the years. An example of these products is the fine electrode foil which will be used in a detector for a particle physics experiment.

Now, International Linear Collider (ILC), a next-generation particle physics experiment project has proceeded, and this new experiment is drawing attention around the world. The purpose of this experiment is to observe various particles created by collisions between electrons and positrons accelerated by a linear accelerator with a total length of about 30 km. A detector to observe these particles with high accuracy is under development through international cooperation [3) 4)]. One of the important challenges regarding the detector is the development of a fine electrode foil [5)].

We succeeded in developing a fine electrode foil for the first time in the world by applying FPC production techniques. This report provides the results of the development in the following chapter.

2. Fine electrode foil

The fine electrode foil used in the detector has many small densely-arranged through holes on the copper clad laminate (CCL). The CCL has a structure in which copper foils are laminated to both sides of an insulation layer [6)]. Table 1 shows specifications required for the structure of the fine electrode foil. They include a through hole diameter less than 300 um, a 170 mm x 220 mm through hole area to ensure an aperture ratio greater than 80% on the CCL with an insulation layer less than 25 um in thickness.

Other companies tried to develop this fine electrode foil, but it seems unlikely that any of them successfully developed the foil that satisfies the required specifications.

In FPC production, forming small through holes in a CCL is an established technique. However, through holes with a diameter smaller than 300 um need to be very closely arranged to achieve an aperture ratio of over 80%. In addition, these through holes need to be uniformly arranged in a 170 mm x 220 mm area.

These requests are very challenging, considering current FPC production technique levels. So we worked on the development of the fine electrode foil after devising a new through hole forming method in addition to the current one in FPC production.

3. Evaluation of fine electrode foil forming method

3.1 Laser drilling

Laser drilling method is one of the current thorough hole forming methods in FPC production. In this method, through holes are drilled in copper and an insulation material (polyimide) at the same time by irradiating the CCL with a beam of a UV-YAG laser

Table 1. Required specifications of the fine electrode foil.

	Requirement specs	Another company's product
Hole size	≦300 μm	90 μm
Insulator thickness	≦25 μm	25 μm
Distance between holes	≦35 μm	50 μm
Optical aperture ratio	≧80%	37%
Foil size	170 mm x 220 mm	100 mm x 100 mm

1 Printed Circuit Technology R&D Department

with a 355 nm wave length. Using this method, a fine electrode foil was created as shown in Fig. 1. Since the beam size of the UV-YAG laser on the work surface is about 20 um to 30 um, the laser beam was moved within a 300 um-diameter circle. The through holes were staggered at an angle of 60°.

Figure 2 shows the fine electrode foil produced by the laser drilling method. The minimum distance between holes of the front side (laser irradiation side) is 14 um and the back side is 28 um, and the average hole diameter of the back side is 302 um. The aperture ratio is about 75%, which fell short of the required value. The irradiated area is 10 mm x 10 mm.

The aperture ratio is calculated from the hole diameter of the back side because the diameters of through holes on the front side are larger than those on the back side. The minimum distance between holes need to be narrower to obtain an aperture ratio greater than 80%. However, the copper electrodes tend to peel off from the polyimide sheet when the minimum distance between holes is less than 10 um. Therefore, it is difficult to process the fine electrode foil with an aperture ratio greater than 80% using the above-mentioned method.

On the other hand, instead of using circle holes, hexagonal holes staggered at a 60° angle (honeycomb structure) enable a 85% aperture ratio in calculation, maintaining the same minimum distance. However, the UV-YAG laser machine is unable to form any shapes other than circles because the machine is optimized for FPC production, and thus it is not realistic to drill honeycomb holes one by one, considering processing accuracy and time. So we concluded that the laser drilling method is not suitable to produce the fine electrode foil.

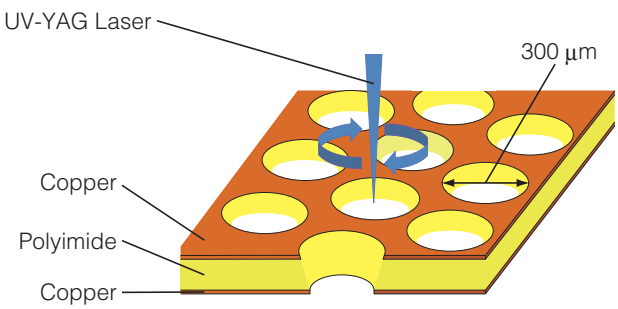

Fig. 1. Image of laser drilling method.

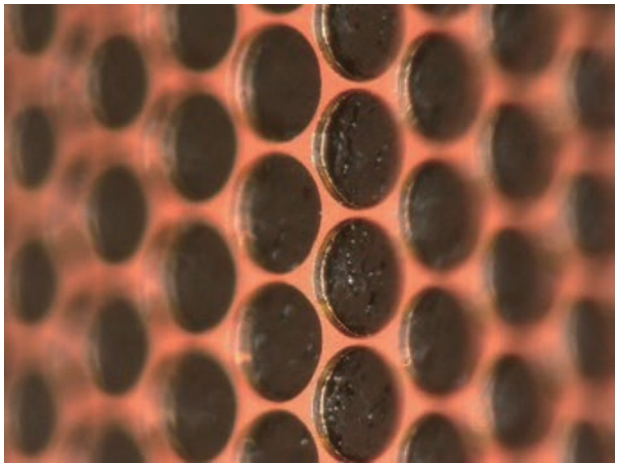

Fig. 2. Fine electrode foil formed by laser drilling.

3.2 Photolithography

Figure 3 shows a BVH (blind via hole), which does not penetrate through the entire CCL and is used for interlayer connection. A BVH forming method offers a greater flexibility in the hole design of the front-side copper by using photolithography and etching. This method also enables the forming of holes in a honeycomb shape. In the next step, the polyimide film is removed by laser or other polyimide removing methods using the remaining copper on the front side as a mask. However, because BVHs do not go through the entire layer thickness, it is necessary to devise a method to remove the copper at the bottom of BVH.

3.2.1 Photolithography using nickel plating

We have invented a method of removing copper at the BVH bottom by plating nickel on the formed copper circuit with a honeycomb structure and using it as a mask for etching copper. As shown in Fig. 4, the honeycomb structure circuit is formed on the front side, and the surface of the circuit is plated with nickel. The polyimide film is removed by a UV-YAG laser using the formed circuit as a mask for laser light irradiation. After the removal of the polyimide, the back side is covered by a film to protect the copper

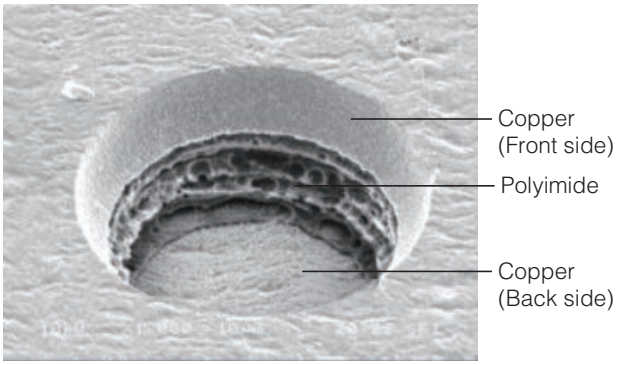

Fig. 3. Appearance of BVH.

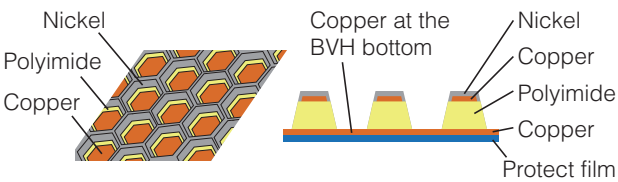

Fig. 4. Electrode forming steps.
(Left: front side appearance image, Right: Cross-section image)

from being etched away so that only the copper at the BVH bottom is etched away by a copper etchant. Because the circuit of the front side is covered by a nickel layer, the circuit is not etched by the copper etchant. Consequently, the copper at the bottom of the BVHs is selectively etched, and through holes are formed.

Figure 5 shows the fine electrode foil processed by photolithography and nickel plating. The average hole diameter on the back side is 295 um, the distance between the holes 25 um (front side) and 36 um (back side), and the thickness of the polyimide 12.5 um. The thinner the polyimide is, the better the performance of the detector is, so the thickness of polyimide was changed from 25 um to 12.5 um. The aperture ratio is approximately 80%, and the processed area is 30 mm x 30 mm.

On the front side of the electrode shown in Fig. 5, there are black spots, where some part of the electrode has come off from the polyimide film. Figure 6 shows the cross section view of the fine electrode foil. There is a gap between the electrodes and polyimide because the copper under the nickel layer was etched.

This problem seems to have occurred because the copper that was designed to be protected was etched away due to the invasion of the copper etchant under the nickel plating during copper etching at the BVH bottom. If such gaps exist, adhesive strength between the electrode and polyimide film drops significantly, and the electrode peels off easily. Considering this problem, we concluded that the BVH forming method combining photolithography and nickel plating is not suitable to produce the fine electrode foil.

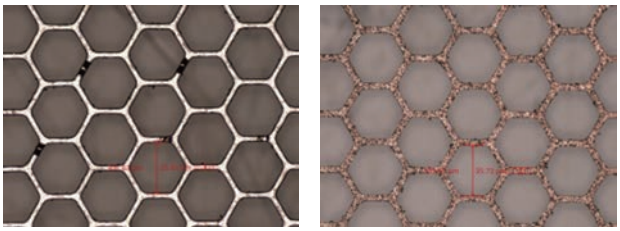

Fig. 5. Fine electrode foil formed using photolithography and nickel plating.
(Left: front side, Right : back side)

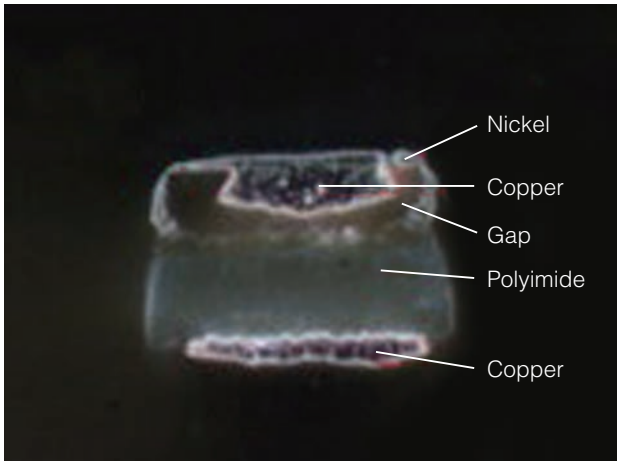

Fig. 6. Cross section of fine electrode foil formed using photolithography and nickel plating.

3.2.2 Photolithography using etching speed

We evaluated a method of creating through holes without using nickel plating, instead, using a CCL of different copper thicknesses and different etching speeds. The copper on the front side is thicker than that on the back side. First, a honeycomb-structure circuit was formed on the front-side CCL, and the polyimide film was removed by UV-YAG laser using the formed circuit as a mask for laser light irradiation. Next, the copper at the BVH bottom was removed to make through holes by etching copper on both sides.

In this etching process, the etching speed at the bottom of BVH is faster than that at the top side because both sides of the BVH bottom are etched (Fig. 7). This makes removing the copper at the BVH bottom possible while a sufficient amount of the copper electrode is left at the top. In addition, the design of the front-side electrode of sufficient copper thickness facilitates the formation of an electrode in an appropriate shape.

Figure 8 shows the fine electrode foil processed by a photolithography using etching speed. The hole diameter on the back side is 304 um, the distance between holes 27 um (front side) and 31 um (back side), the thickness of polyimide 12.5 um, and the processed area 100 mm x 100 mm. There exists no peeling off of the electrode from the polyimide film as

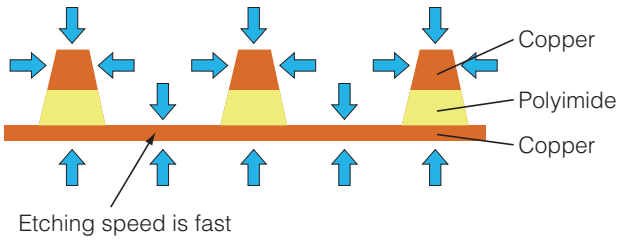

Fig. 7. Image of through hole forming using etching speed.

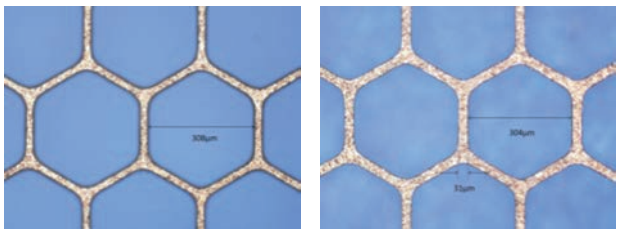

Fig. 8. Fine electrode foil processed by photolithography using etching speed.
(Left: front side, Right: back side)

mentioned in “3.2.1 photolithography using nickel plating”. The aperture ratio is 82%, which satisfies the required aperture ratio of 80%.

4. Limitations of fine electrode foil processing

We examined the limitations of the fine electrode foil processing by photolithography taking etching speeds into consideration.

4.1 Evaluation of 170mm x 220mm size

The size required for the fine electrode foil is 170 mm x 220 mm as shown in Table 1, and this size is much larger than that of a standard FPC. The problem in processing a fine-electrode in a large size is breaks in the honeycomb-structure circuit formed by photolithography and etching on the front side. If a circuit break occurs, the polyimide film under the electrode is exposed and eventually removed by the laser, which will cause a break in the whole electrode. A fine electrode foil of 170 mm x 220 mm size without circuit breaks has been successfully produced by improving production environments and using new processing materials.

Figure 9 shows the 170 mm x 220 mm-size fine electrode foil for the detector. From the evaluation results above, we think the limit of processing area is up to about 240 mm x 300 mm.

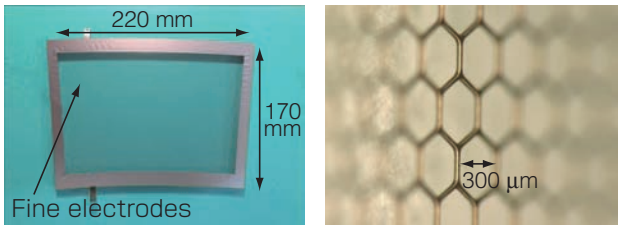

Fig. 9. 170 mm x 220 mm-size fine electrode foil.
(Left: appearance, Right: micrographs of electrodes)

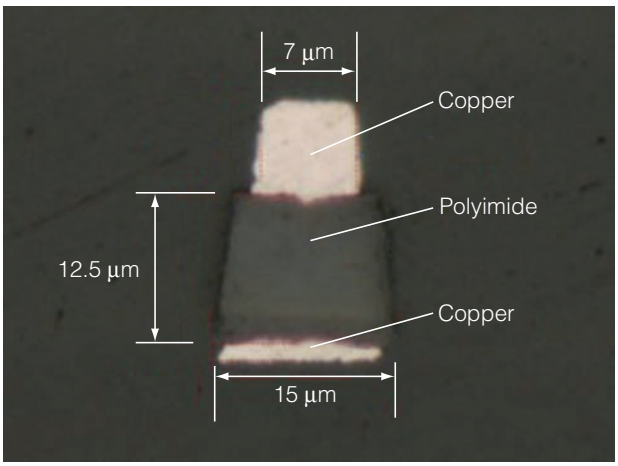

Fig. 10. Cross-section view of the fine electrode foil.

4.2 Minimum distance between holes

The larger an aperture ratio of the fine electrode foil, the better the performance of the detector. We examined to what extent the minimum distance between the holes can be shortened to get a higher aperture ratio.

Reducing the distance between the holes causes the adhesive strength between the electrode and polyimide film to drop and thus the electrode to peel off. So far, we have determined that the peeling of the electrode of the front side starts when the distance between the holes is less than 7 um. Taking this into account, the minimum distance between the holes is about 15 um on the back side as shown in Fig. 10.

4.3 Minimum hole size

Furthermore, regarding the size of the through holes, the smaller the size is, the better the performance of the detector is. Figure 11 shows the test sample with a 100 um hole diameter and 20 um distance between the holes. In creating a small hole with a diameter less than 100 um, it is difficult to form a honeycomb-structured circuit by photolithography and etching, and the hole shape is close to a circle. In this case, the aperture ratio reduces for the same reason as mentioned in “3.1 Laser drilling”. Therefore, we think that the minimum hole diameter should be about 150 um, considering our current manufacturing ability.

5. Test results of the fine electrode foil mounted to detector

We made a sample as shown in Table 2 based on the evaluation results of each processing method and limitations of the processing method.

The sample has been mounted to the prototype of the detector for particle observation and tested for its

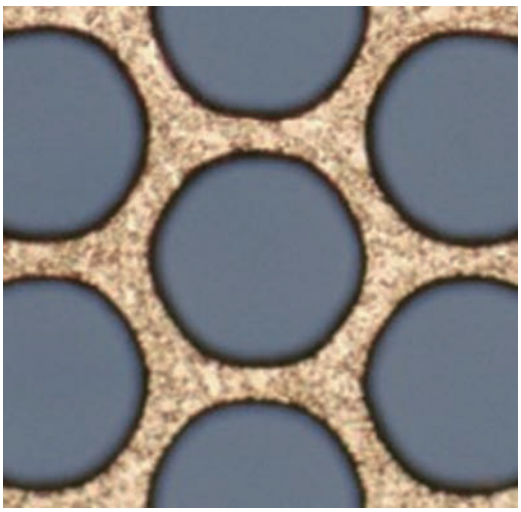

Fig. 11. Micrographs of fine electrode foil.
(Hole diameter: 100 um, Distance between holes: 20 um)

Table 2. Required specifications for the fine electrode foil and specifications of our prototype.

	Requirement specs	Our prototype
Hole size	≦300 μm	304 μm
Insulator thickness	≦25 μm	12.5 μm
Distance between holes	≦35 μm	31 μm
Optical aperture ratio	≧80%	82%
Foil size	170 mm x 220 mm	170 mm x 220 mm

performance. In this test, we checked that the sample worked properly and delivered expected performance. Consequently, we think that we have successfully developed the fine electrode foil that satisfies the required specs using the production method we devised.

6. Conclusion

We have succeeded in developing the fine electrode foil, which has an aperture ratio greater than 80%, of the detector for particle physics experiments by applying the FPC production techniques.

We will continue to apply our FPC production techniques in various fields.

References

1) M.Ikeda, et al, "Techniques of fine circuit fabrication," Fujikura technical review (Japanese version), No. 115, pp38-41, 2009
2) K.Kobayashi, "Advanced flexible printed circuits technology," Fujikura technical review, No. 42, pp44-47, 2013
3) ILC Reference Design Report, http://www.linearcollider.org/rdr.
4) R.yonamine, et al. JINST. 7, C06011 (2012)
5) D.Arai, Master thesis (2012), Tokyo University of Agriculture and Technology (TUAT)
6) P.Gros, et al. JINST 8, C11023 (2013)
7) K. Ikematsu on behalf of the LCTPC-Japan Collaboration, IEEE(NSS/MIC) 2014 Conference Record (N44-7)