Development of gating foils to inhibit ion feedback using FPC production techniques

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  - Processing method
  - Development results
    Laser drilling
    Single mask

• Limit of Gating foil processing
  - Large size processing
    170mm x 220mm size
  - Fine electrode processing
    Minimum rim width and hole size

• Summary
- Positive Ion Feedback in ILC TPC
  - Time Projection Chamber (TPC) with MPGD readout is proposed to be the central tracker of ILD detector for the International Linear Collider (ILC).
  - Positive-ion feedback from the gas-amplification region to the drift region can deteriorate the position resolution of TPC.
  - Required point resolution of better than 100 μm for long drift (~2.3 m) @3.5T

Fig 1-1. ILC beam structure

Fig 1-2. Positive ion feedback in ILC TPC

Distortion of the reconstructed track
Maximum 90um (Simulation results)
• **Gating foil for ILC TPC**
- Mounting the Gating foil near the MPGD to stop the feedback of positive ions.

![Gating foil diagram](image)

- Gating foil have GEM-like structure.
- Gating foil is operated in low voltage mode. *(initially proposed by F. Sauli in 2006)*
- Gating foil can easily be used as a closed gate by reversing the electric field.

![Gating foil images](image)
**Requirement for Gating foil**

- **Requirement for Gating foil of ILC TPC**
  - 80% electron transmission is required to satisfy the performance of ILC-TPC.
  - Endplate of ILC-TPC is consist of 240 modules, and 1 module size is 170mm x 220mm.
  - From the simulation results by ILC-TPC group, the Gating foil is required according to the below spec.

<table>
<thead>
<tr>
<th>Item</th>
<th>Gating foil</th>
<th>Amplification GEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical aperture ratio</td>
<td>≥80%</td>
<td>22.7%</td>
</tr>
<tr>
<td>Hole size</td>
<td>≤300μm</td>
<td>70μm</td>
</tr>
<tr>
<td>Hole pitch</td>
<td>≤335μm</td>
<td>140μm</td>
</tr>
<tr>
<td>Rim width</td>
<td>≤35μm</td>
<td>70μm</td>
</tr>
<tr>
<td>(Hole pitch - Hole size)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulator thickness</td>
<td>≤25μm</td>
<td>50μm or 100μm</td>
</tr>
<tr>
<td>Foil size</td>
<td>170mm x 220mm</td>
<td>170mm x 220mm</td>
</tr>
</tbody>
</table>

Table 1. Requirement spec for Gating foil and Amplification GEM of ILC TPC
Production techniques of FPC and GEM

- Why does Fujikura try to develop the Gating foil?
  - Fujikura is one of major Flexible Printed Circuit (FPC) makers in the world.
  - FPC is commonly applied to cables inside electrical appliances.
  - Production techniques of GEM are the same as FPC production techniques.

Table 2. Relationship between GEM and FPC

<table>
<thead>
<tr>
<th>GEM production</th>
<th>Key techniques</th>
<th>FPC production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single mask</td>
<td>Photolithography</td>
<td>Circuit formation</td>
</tr>
<tr>
<td>Double mask</td>
<td>Insulator removing</td>
<td></td>
</tr>
<tr>
<td>Laser drilling</td>
<td>Laser processing</td>
<td>Making through hole</td>
</tr>
</tbody>
</table>

FPC (Flexible Printed Circuit)
Key techniques of Gating foil production

Production method of Double Layer FPC

1. Laminate the photoresist film on the CCL (Copper Clad Laminate)
   - Photoresist film
   - Copper
   - Polyimide
   - Copper

2. Expose the film using the photo mask
   - Light
   - Photo mask
   - Cured by light

3. Photoresist development
   - Developer
   - Etching mask

4. Etching and remove the photoresist
   - Etcher
   - Circuit
   - Remover
Our Goal

Key techniques of Gating foil production

- Production method of Double Layer FPC

5. Remove the polyimide using the copper as etching mask

6. Plating copper on the surface of polyimide to contact the circuit on both layers

Laser mask

Many other process

GEM   Gating foil

FPC

Our Goal
Develop the Gating foil for ILC-TPC and solve the Positive ion feedback problem using the FPC production techniques.
• **Difficulty of Gating foil production on each process**
  - We tried to study about 3 production methods.

<table>
<thead>
<tr>
<th>GEM production</th>
<th>Key technique</th>
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<tbody>
<tr>
<td>Single mask</td>
<td>Photolithography</td>
</tr>
<tr>
<td>Double mask</td>
<td>Insulator removing</td>
</tr>
<tr>
<td>Laser drilling</td>
<td>Laser processing</td>
</tr>
</tbody>
</table>

Table 3. GEM production methods

1. **Double mask process**
  - Double mask process need the photomask alignment, but the accuracy of the alignment is about ±10μm over a large area.

Distorted structure of electrode can't make the electric field collectively.

Fig 5. Image of rim (Double mask process)
2. Laser drilling process
- UV-YAG Laser is usually used in making through hole (TH) of FPC.
- Gaussian beam mode of UV-YAG Laser can process copper and polyimide at the same time.
  (beam size of Gaussian mode beam: 20~30μm)
- We confirmed the minimum rim width on Laser drilling process.

Fig 6. Image of Laser drilling process
2. Laser drilling process

- Minimum rim width is 28μm. (Under 35μm)
- The rim didn't break and maintained the fine structure. (Pic.1)
- Copper removed from the polyimide on the F-side rim width 10μm. The limiting width of the rim by Laser drilling process is 25μm.
- Optical aperture ratio was 75%. (Under 80%)
- Processing time of 10mm x 10mm was 6min. In case of 170mm x 220mm, the processing time is about 2,240min...
2. Laser drilling process

- Circle structure Gating foil couldn't reach optical aperture ratio 80%.
- The Laser machine for FPC products is optimized to circle processing.

**Fig 7.** Relationship between Rim size and Optical aperture ratio on 335μm hole pitch

*Laser drilling process isn't suitable for the Gating foil processing*
3. Single mask process
- Single mask process usually use Ni-plating as the etching mask for B-side copper etching.
- Gating foil is used in a magnetic field 3.5T, so we don't want to use Ni.
- So we need to develop a "No Ni plating single mask process".

- **No Ni plating Single mask process**
  
  (1) Laminate the photoresist film on CCL

![Diagram](image1)

  - Photoresist film
  - Copper (Thick)
  - Polyimide
  - Copper (Thin)

(2) Form Honeycomb structure circuit on the **thick copper side**

![Diagram](image2)

- Copper (Thick)
- Polyimide
- Copper (Thin)
Single mask – Process (Insulator removing)

3. Single mask process

(3) Remove the polyimide by UV-YAG Laser

- Why we select the UV-YAG Laser?
  - Laser have **higher processing accuracy** and can process the **higher angle-taper hole** than the polyimide etching.
  - UV-YAG Laser can remove polyimide **with small damage**. (better for making narrow rims)

Pic 2. Damage of polyimide by UV-YAG Laser and CO2 Laser
3. Single mask process

(4) Etch the copper from both side by etching liquid

```
Etching speed is 2 times faster
```

- **Point of No Ni-plating Single mask process**
  - **Process is very simple**, so the process has an advantage for the large area processing.
  - We need to control copper thickness of F-side and B-side and the amount being etched is very severe.
## 3. Single mask process

### Results

<table>
<thead>
<tr>
<th>Item</th>
<th>Gating foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole size</td>
<td>304μm</td>
</tr>
<tr>
<td>Hole pitch</td>
<td>335μm</td>
</tr>
<tr>
<td>Rim width: F-side</td>
<td>27μm</td>
</tr>
<tr>
<td>Rim width: B-side</td>
<td>31μm</td>
</tr>
<tr>
<td>Insulator thickness</td>
<td>12.5μm</td>
</tr>
<tr>
<td>Size</td>
<td>100mm x 100mm</td>
</tr>
<tr>
<td>Processing time</td>
<td>70min (only laser)</td>
</tr>
<tr>
<td>Optical aperture ratio</td>
<td>82.3%</td>
</tr>
</tbody>
</table>

Many problems happened...

Pic3-1. Problem 1: Effect of copper grain size

Pic3-2. Problem 2: Effect of contact surface treatment on copper

Pic3-3. Surface of F-side

Pic3-4. Surface of F-side

Pic3-5. Cross section of rim
3. Single mask process

We developed the Gating foil which optical aperture ratio is over 80% on 100mm x 100mm size with No Ni-plating single mask process!

We established the stable process, and we tried to develop 2 items.
(1) Large size processing
(2) Fine electrode processing
**Large size processing: Recent situation**

- **Difficulty of Large size Gating foil production**
  - We already developed the 170mm x 220mm size Gating foil with the No Ni-plating process.
  - But there were a few electrode breaks in the Gating foil we developed.
  - No electrode breaks are required for the 170mm x 220mm size.
  - The cause of the electrode breaks is contamination on Photolithography process (=circuit formation process).

Pic5-1. Gating foil 170mm x 220mm size (but include a few electrode breaks)

Pic5-2. Circuit break after circuit formation
Large size processing: Problem

- **Difficulty of Large size Gating foil production**
  - Cause of circuit breaking
  - The cause of circuit breaking is due to contamination on 4 possible places.
  - The size of contamination is a few tens of μm.

(1) Under the photoresist  (2) On the photoresist  (3) Below the photomask  (4) On the photomask

We already solved this problem by improving the cleanness of processing environment and optimization the photoresist.
How fine can we process the electrodes?

- We tried to process more fine electrodes using No Ni-plating single mask process.
- This time we processed only 30mm x 30mm size.
- We confirmed the diameter of the Gating foil holes of on 100μm, 150μm and 200μm.

**Minimum rim width**

(1) φ205μm, 225μm pitch, Rim width : 20μm, Polyimide 12.5μm

- Rim width : F-side 14μm, B-side 20μm
- We can process 20μm rim width and φ200μm honeycomb structure holes.
Processing of Fine electrodes: Minimum rim width

- How fine can we process the electrodes?
  - Minimum rim width

(2) φ153μm, 168μm pitch, Rim width: 15μm, Polyimide 12.5μm

- F-side electrode width was 7μm.
- Copper was stripped from polyimide when the electrode width was about under 7μm.

We confirmed the minimum rim width is 15μm.
Processing of Fine electrodes: Minimum hole size

- How fine can we process the electrodes?

**Minimum hole size**

(3) φ97μm, 120μm pitch, Rim width: 23μm

- Etching liquid etch the copper isotropically.
- It is difficult to make sharp edge especially for the small hole.

We can't process the honeycomb structure hole with a hole size of less than 150 μm
• ILC-TPC is planned to be equipped with a gating foil to inhibit the positive ion feedback.

• Gating foil like GEM structure which optical aperture ratio is over 80% is required.

• We tried to develop the Gating foil using FPC techniques especially Photolithography and Insulator removing.

• We developed the Gating foil with optical aperture of greater than 80% on 100mm x 100mm size with the No Ni-plating Single mask process.

• Large size (170mm x 220mm) processing had a problem with circuit breaking, but we already solved this problem.

• We confirmed the minimum rim width and hole size on 30mm x 30mm size. (minimum rim width : 15μm, minimum hole size 150μm)
Thank you for your attention

Pic. Inspection of Circuit breaks by AOI (Automated Optical Inspection) machine
Back up
1. Electron transmission

(1) Measurement method of Electron transmission

by comparing signal charge passing through the Gate-GEM to signal without Gate-GEM using a small test chamber irradiated with an 55Fe source, which is installed in a 1T MRI type super-conducting solenoid at KEK cryo center.

- Case (2): the conversion happens in the drift region, so that the produced electrons have to pass the gate and the signal is affected by the gate transmission.

- Case (1): a small portion of the X-rays are converted in the region between the gate and the amplification GEM, which produces signal without any effect of the gate.

- Electron transmission: calculated as the ratio of the two signals.

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
1. Electron transmission Measurement

(2) Results of Electron transmission

- We confirmed the electron transmission of the honeycomb structure is over 80%.

(2-1) Circle structure Gating foil (Optical aperture ratio: 75.8%)

(2-2) Honeycomb structure Gating foil (Optical aperture ratio: 82.3%)

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
1. Electron transmission Measurement

(3) Simulation results of electron transmission

**ANSYS-Garfield++ simulation (0 T, $V_{gate} = 20$ V)**

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
1. Electron transmission Measurement

(3) Simulation results of electron transmission

ANSYS-Garfield++ simulation ($B = 1$ T, $V_{gate} = 20$ V)

Preliminary

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
(3) Simulation results of electron transmission

**ANSYS-Garfield++ simulation (3.5 T, V_{\text{gate}} = 20 V)**

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
1. Electron transmission Measurement

(3) Simulation results of electron transmission

- From the simulation results, we can get over 80% electron transmission in the magnetic field 3.5T.

(2-1) Circle structure Gating foil
- Optical aperture ratio: 75.8%

(2-2) Honeycomb structure Gating foil
- Optical aperture ratio: 82.3%

Refer from "Development of Large-Aperture GEMs as a Gating Device of ILC-TPC for Blocking Positive Ion Feedback" Katsumasa Ikematsu (Saga Uni.)
2. Ni-plating Single mask process

(1) Process

(1) Form the honeycomb circuit

(2) Plating Ni on the circuit of F-side

(3) Remove the polyimide by UV-YAG Laser

(4) Laminate the cover film on B-side, and etch the copper.

(5) Remove the cover film

Only etch the hole position
2. Ni-plating Single mask process

(2) Results

<table>
<thead>
<tr>
<th>Item</th>
<th>Gating foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole size</td>
<td>295μm</td>
</tr>
<tr>
<td>Hole pitch</td>
<td>330μm</td>
</tr>
<tr>
<td>Rim width: F-side</td>
<td>25μm</td>
</tr>
<tr>
<td>Rim width: B-side</td>
<td>35μm</td>
</tr>
<tr>
<td>Insulator thickness size</td>
<td>12.5μm</td>
</tr>
<tr>
<td>size</td>
<td>30mm x 30mm</td>
</tr>
<tr>
<td>Processing time</td>
<td>10min (only laser)</td>
</tr>
<tr>
<td>Optical aperture ratio</td>
<td>80.0%</td>
</tr>
</tbody>
</table>

![Pic11-1. F-side](image1)

![Pic11-2. B-side](image2)

![Pic11-3. Cross section](image3)

- Etching liquid etch the copper under the Ni
- Copper stripped from the surface of polyimide
(2) Results

<table>
<thead>
<tr>
<th>Item</th>
<th>Gating foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole size</td>
<td>275μm</td>
</tr>
<tr>
<td>Hole pitch</td>
<td>315μm</td>
</tr>
<tr>
<td>Rim width: F-side</td>
<td>30μm</td>
</tr>
<tr>
<td>Rim width: B-side</td>
<td>40μm</td>
</tr>
<tr>
<td>Insulator thickness size</td>
<td>12.5μm</td>
</tr>
<tr>
<td>Optical aperture ratio</td>
<td>76.0%</td>
</tr>
</tbody>
</table>

Pic12-1. F-side
Pic12-2. B-side

- We need to plate thick-Ni to protect the copper circuit.
- ILC-TPC is used in the high magnetic field 3.5T, so we don't use the Ni.
- Polyimide expose when we strip the Ni. (we can't make the collective electric field)
- Ni-plating Single mask isn't suitable for the Gating foil processing.
3. CO2 Laser and UV-YAG Laser

- Processing method of CO2 laser is "Thermal processing" and UV-YAG laser is "Ablation".
- Ablation is Non-thermal processing, so we can process the polyimide with small damage.

<table>
<thead>
<tr>
<th>Laser source</th>
<th>Wave length</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>10.6μm</td>
<td>Thermal processing</td>
</tr>
<tr>
<td>UV-YAG</td>
<td>355nm</td>
<td>Ablation</td>
</tr>
</tbody>
</table>

Laser ablation
Laser ablation is the process of removing material from a solid (or occasionally liquid) surface by irradiating it with a laser beam. At low laser flux, the material is heated by the absorbed laser energy and evaporates or sublimates. At high laser flux, the material is typically converted to a plasma. Usually, laser ablation refers to removing material with a pulsed laser, but it is possible to ablate material with a continuous wave laser beam if the laser intensity is high enough.
4. Accuracy of Single mask processing

Measurement results

• We confirmed the processing accuracy of electrodes on the No Ni-plating Single mask process.
• We measured the rim width on 5 position (center and 4 corners) in 3 samples.

Fig6. Measurement position
4. Accuracy of Single mask processing

Measurement results

<table>
<thead>
<tr>
<th></th>
<th>Rim width (um)</th>
<th>Copper thickness(um)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-side</td>
<td>B-side</td>
</tr>
<tr>
<td></td>
<td>F-side</td>
<td>B-side</td>
</tr>
<tr>
<td>ave.</td>
<td>26.74</td>
<td>30.96</td>
</tr>
<tr>
<td>Max-Min</td>
<td>6.87</td>
<td>7.27</td>
</tr>
<tr>
<td>3σ</td>
<td>4.66</td>
<td>5.03</td>
</tr>
</tbody>
</table>

Sample No. | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
---         | ---     | ---     | ---     | ---     | ---     |
1          | ![Image 1](image1) | ![Image 2](image2) | ![Image 3](image3) | ![Image 4](image4) | ![Image 5](image5) |
2          | ![Image 6](image6) | ![Image 7](image7) | ![Image 8](image8) | ![Image 9](image9) | ![Image 10](image10) |
3          | ![Image 11](image11) | ![Image 12](image12) | ![Image 13](image13) | ![Image 14](image14) | ![Image 15](image15) |
5. Distortion of Ion Feedback

Simulation results

- Distortion of the reconstructed track is Maximum 90μm.

Fig7-1. Simulation results of disitortion from Ion Feedback

引用文献“Simulation of Field Distortions because of Ion Back Drift” Thorsten Krautscheid
Material for Gating Foil

- CCL is a basic material on the FPC production.
- We can select 3 types of CCL.
- We need to use the 2Layer CCL for Gating foil production, because adhesive layer easily be damaged by Laser.
- Treatment on the contact surface of copper is very important for the B-side copper etching processing.

(1) 3 Layer CCL
(2) 2 Layer CCL
(3) Sputter CCL

Some material plating on the copper
(Material maker confidential information)

Roughness: 1um~5um