Progress on large area GEMs

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A B S T R A C T

The Gas Electron Multiplier (GEM) manufacturing technique has recently evolved to allow the production of large area GEMs. A novel approach based on single mask photolithography eliminates the mask alignment issue, which limits the dimensions in the traditional double mask process. Moreover, a splicing technique overcomes the limited width of the raw material. Stretching and handling issues in large area GEMs have also been addressed. Using the new improvements it was possible to build a prototype triple-GEM detector of /C242000 cm\textsuperscript{2} active area, aimed at an application for the TOTEM T1 upgrade. Further refinements of the single mask technique allow great control over the shape of the GEM holes and the size of the rims, which can be tuned as needed. In this framework, simulation studies can help to understand the GEM behavior depending on the hole shape.

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1. Introduction

Gas Electron Multipliers (GEMs) are gaseous charge amplification structures invented in 1997 by Sauli\textsuperscript{1}. Currently they are widely used for a variety of different applications, not limited to high energy physics. However, standard GEM foils larger than \textasciitilde 40 cm are not available, since the manufacturing process becomes difficult when applied to large areas.

Given the increasing demand for large area GEMs, an effort has been started aimed at finding a new GEM production technique that can be scaled up to square meter size. The manufacturing steps have been analyzed and four main bottlenecks have been identified. These are namely the alignment of the two photolithographic masks, the limited size of the raw material and the GEM stretching and handling. Each issue has been studied and a solution has been proposed.

2. Single mask photolithography

The production of GEMs is based on photolithographic techniques commonly used by the printed circuit industry. The raw material is usually 50\textmu m thick kapton, with 5\textmu m copper cladding on both sides. This substrate gets laminated on both sides with solid photoresist of 15\textmu m in thickness, on which the GEM hole pattern is transferred by UV exposure from flexible masks. In order to get a good homogeneity of the hole geometry across the foil, it is very important to keep the alignment error between the two masks within 10\textmu m. However, since both the raw material and the two masks are flexible, the manual alignment procedure becomes extremely cumbersome and involving when the linear dimensions of the GEM exceed \textasciitilde 40 cm.

A natural way of overcoming this problem is the use of single mask photolithography. In this case the GEM pattern is transferred only to one side of the raw material, thus removing any need for alignment. The exposed photoresist is developed and the hole pattern is used as a mask to chemically etch holes in the GEM top copper electrode. After stripping the photoresist, the holes in the top copper electrode are in turn used as a mask to etch the polyimide.

2.1. Etching the polyimide

Developing the single mask technology for GEMs, effort has been put in studying the available polyimide etching chemistries and their characteristics.

A first interesting chemistry is based on potassium hydroxide (KOH) and has a typical isotropic etching behavior. This means that kapton is removed from the raw material at the same rate in all directions. As a result, holes created in this way are always at least twice as large as they are deep. Moreover, this chemistry leads to strong kapton etching under the copper, as schematically shown in the upper part of Fig. 1.

A second chemistry, based on ethylenediamine, has an anisotropic etching behavior, which results in wide conical holes.
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chromic acid [2]. The use of this chemical allows a very
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Using this technique, one can never get cylindrical holes in the
polyimide. Even if it is important to open fairly steep holes, at his
stage the main concern is to define very precisely the shape of the
holes on the bottom of the polyimide. These holes will in fact
constitute the mask for the subsequent bottom copper etching.
The steepness can be increased at a later stage, after etching the
holes on the bottom electrode, by means of a fast kapton etching.

2.2. Etching the bottom copper layer

In single mask photolithography the GEM bottom electrode is
pierced by immersing the foil into an acid solution. All the copper
surfaces are then etched at the same rate. Therefore, the bottom
copper foil is attacked both from the outer surface of from the holes
in the polyimide, which act as a mask.

It was found that a good etching solution is the one based on
chroomic acid [2]. The use of this chemical allows a very
homogeneous etching over large areas, thus minimizing copper
thickness variations. As a consequence, the diameter of the holes
created in the bottom copper layer can be kept constant across
the entire foil, granting a good gain uniformity. Moreover, the
cromic acid leaves very polished and shiny surfaces. This assures
a good hole shape definition and reduces any boundary rough-
nesses that could favor discharges.

As the copper layer is not protected during this process, it
will also be attacked by the acid solution. Due to the isotropic
etching behavior of the chromic acid, a clearance will form around
the edge of the hole in the polyimide. The clearance, usually
known as rim, degrades the time stability of the GEM. Fig. 2 shows
microscope pictures of GEM holes created with the single mask
technique. The hole diameter is about 100 μm at the top surface
and 45 μm at the bottom.

In order not to create the rim at all, one has to protect the
top copper layer during the second copper etching phase. Different techniques have been explored and the best results are
obtained with electrochemical active corrosion protection. In this
procedure, a photoresist layer is laminated on the bottom of the
foil before starting the second copper etching. A negative DC
potential of about −3 V is then applied to the top electrode, while
dipping the foil into a grounded chromic acid bath. Under these
conditions, a direct current flows from the walls of the bath to the
top electrode, thus making it totally inert to the action of the
etching chemical. As a result, only the bottom copper layer will
be etched and only through the holes in the polyimide, which act
as a mask.

In order to reduce even more the amount of exposed kapton,
one has to increase the steepness of the holes. This can be done
with a moderate bottom copper overetching. The process is
stopped only when the diameter of the holes becomes about the
same as the diameter on the top copper electrode. The GEM is
then moved back into the polyimide etching solution for about
30 s to remove the excess polyimide. The result is shown in Fig. 3.
The holes in both copper layers are perfectly defined, without
any delamination. The hole cross-section is almost cylindrical.
The average diameters are 85 μm on the top and 70 μm on the
bottom.

It is advisable to perform a chemical cleaning of the GEM at the
end of the process. This will remove impurities possibly left on the
GEM and will make the foil stronger against sparks.

The foils manufactured in this way can stand high voltages of
up to (650 ± 40) V in air. 10 × 10 cm² specimens were tested in the
form of a double GEM stack. The measurements were performed
in Ar:CO₂ (70:30) using a collimated X-ray beam ( ≥ 1 mm) from a
copper radiation source. Fig. 4 shows the obtained spectrum.
The three peaks, from right to left, represent the K$_{a}$ photopeak,
the argon escape peak and the pedestal. The energy resolution
extracted from the fits is 20.8% FWHM/peak, compatible with the
one of a standard GEM.

Due to the almost cylindrical holes in the polyimide and due to
the absence of rims, a good time stability of the gain is expected.
In order to measure the gain variation over time, many low-
statistics spectra were acquired in sequence. Fig. 5 shows the
normalized gas gain, extracted from the fits to the spectra, as a
function of the time elapsed after the start of the irradiation. The
decay time is 14 ± 4 s, much faster than for standard GEMs, which
require some tens of minutes to stabilize. Also the gain variation
is small compared to standard GEMs: 4% instead of 10%.

The maximum achievable gain of the double GEM is about
4 × 10^{8}; this is not very high, as one can expect from the total
absence of a rim. However, even if these hole parameters are
probably not the best for a GEM-based detector, the single mask
photolithography combined with electrochemical active corrosion
protection has proven to be a mature manufacturing technology.
In fact, it not only allows GEMs to be made, but it also permits to
accurately tune all the hole parameters within a certain range by
changing the details of the applied etching chemistry.

3. Splicing GEMs

At present, the GEM base material comes in rolls 100 m long
and 457 mm wide. A new provider has been found that would be
able to deliver rolls with 600 mm width. However, even the wider
foils would not be enough to satisfy the requirements of some of
the possible applications. The splicing technique was introduced
to accommodate these needs.

GEM foils can be spliced together by means of two 2 mm wide
kapton cover layers, one on each side of the GEMs. Each cover
layer is carefully aligned along the GEMs’ edges and then fixed in

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place by applying pressure at 240°C. The resulting seam is flat, regular, mechanically and dielectrically strong.

Fig. 6 shows a microscope picture of two GEM foils tightly joined using the splicing technique. The plot superimposed on the picture is a rate scan performed across the seam using a collimated X-ray beam (Δ0.5 mm). The dead region is only ~2 mm wide. Moreover, the rest of the GEMs' active area behaves normally, remaining unaffected by the splicing procedure.

By combining the single mask photolithography with the splicing technique it was possible to build a large area triple GEM detector. This prototype, intended as a possible upgrade of the TOTEM T1 tracker [3], has an active area of ~2000 cm² and it is based on 66 × 66 cm² GEM foils, obtained splicing together two single mask GEMs [4].

4. Stretching GEMs

Stretching is an important step in the assembly of GEM foils. At present there are two main techniques:

The first possibility is thermal stretching. In this case the GEM is fixed to a plexiglass frame and then inserted into an oven, in which the temperature is increased by some tens of degrees. The thermal expansion of the plexiglass will uniformly stretch the foil, that can then be glued to its frame.
A different approach relies on mechanical stretching. This method employs specially designed benches featuring clamps along all the edges, on which the GEM foil can be fixed. The clamps are connected to load cells and the applied tension is read by meters connected to the cells.

Both techniques become somehow problematic when applied to large area GEM foils. In order to make the assembly of GEM-based detectors simpler, new ideas are being explored that would avoid the stretching phase at all. For example, honeycomb structures can be used to keep the distance between unstretched foils. This has been shown to work on a test chamber. Optimization studies are at present ongoing to determine the best honeycomb cell size and the corresponding amount of introduced inefficiency. The gas flow in the chamber is also under investigation, to understand how it is modified by the honeycomb spacers.

5. Handling GEMs

Some of the production steps of single mask GEMs take place in chemical baths which have finite dimensions. In order to fit large foils into these baths, a stainless steel foldable portfolio was designed and produced. It can house a foil with dimensions of up to 200 cm x 50 cm and, since it has no plastic parts and no lubricants, it can be immersed in the etching liquids together with the foil it holds.

A further improvement will come from the planned upgrade of the CERN workshop. Due to the absence of labor-intensive manual interventions, namely the alignment of the photolithographic masks, single mask GEMs can be produced using roll-to-roll equipment. A roll-to-roll compatible copper micro-etching machine and a polyimide etching machine are foreseen for installation in the CERN workshop by the end of 2010. This will open the way to the production of large area GEMs without the need for chemical baths. Moreover, it will allow knowledge to be gained on large scale production issues, in view of a future large scale production in collaboration with industry.

6. Investigating different hole shapes

The manufacturing procedures described in Section 2 allow the desired hole diameter on the top and on the bottom copper layers to be chosen, as well as the size of the rim around the holes in the two electrodes. But it is not yet clear what would be the optimal shape of the holes, and what the best orientation (with the larger diameter towards the anode or towards the cathode). Moreover, the optimal shape and orientation depend on which properties have to be optimized. In this framework, simulations can help to gain some knowledge.
A simulation effort has been started in this direction. The Ansys\(^2\) package was used to describe the hole geometry and to numerically compute the electrical field in the problem domain using a finite element method. The so generated fieldmap was fed to Garfield\(^3\) which was then used to visualize the field and to drift the electrons in the selected gas mixture. Fig. 7 shows how the equipotential lines and the electric field lines change depending on the geometry.

Fig. 8 represents the electron end point distribution as a function of the hole geometry. For each configuration, 1000 electrons were created 70\(\mu\)m above the GEM, with random initial coordinates along the\(x\)- and \(y\)-axes. The electrons were drifted using the Garfield microscopic tracking function and the final positions were recorded. The drift field and the induction fields were set to 3 kV/cm and the potential difference across the GEM was 400 V. The gas mixture was \(\text{Ar:CO}_2\) (70:30) at 300 K and atmospheric pressure. The plot indicates that the percentage of electrons collected on the top GEM electrode increases as the hole's top diameter decreases. The number of electrons ending up on the kapton decreases moving from a larger diameter on the top to a larger diameter on the bottom. The overall electron transparency, indicated by the percentage of electrons reaching the anode, is not strongly affected by the hole shape in the studied range.

7. Conclusions

The single mask photolithography has proven to be a valid manufacturing technique for making GEMs. Exploiting this technology it has already been possible to build a prototype detector for a possible upgrade of TOTEM T1. More recently, the production process has been refined even more, giving great control over the dimensions of the GEM holes and the size of the rims. Simulation studies are ongoing, to gain knowledge on the effects of the hole shape. Production issues have been studied and single mask GEMs are compatible with industrial production using roll-to-roll equipment. A price reduction is expected from industrial large scale production.

References