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(57) Abstract: A method of manufacturing, at least in part, a gas electron multiplier, GEM, is described. At S101, the method comprises providing a precursor, comprising a substrate, for example a sheet or a plate, having opposed first and second surfaces. At S102, the method comprises masking the first surface of the precursor using a first mask defining a first set of apertures, including a first aperture, at least partly therethrough. At S103, the method comprises perforating the masked precursor, thereby forming a set of perforations, including a first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures; wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures. A GEM is also described.

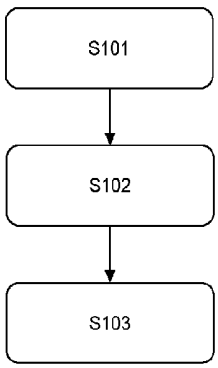

Fig. 1

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APPARATUS AND METHOD

Field

The present invention relates to gas electron multipliers.

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Background to the invention

Generally, a gas electron multiplier (GEM) (also known as a GEM electrode) is a type of gaseous ionization detector, particularly a micropattern gaseous ionization detector, typically used in nuclear and particle physics for position detection of ionising radiation such as charged particles, photons, X-rays and neutrons.

A GEM typically comprises a relatively thin polymer foil substrate (typically 50 to 70 μm thickness), for example Kapton (RTM), metal-coated (for example copper) on both sides and perforated with a relatively high number density (typically 50 to 100 mm^{-2}) of relatively small holes (typically 30 to 50 μm diameter), as manufactured by photolithography and chemical etching processes, for example. The GEM is typically installed between a drift electrode and a charge collection electrode. By applying a large potential difference across the foil, a high electric field is created in the holes such that electrons, for example generated by ionization events, drift towards the holes and acquire sufficient energy to cause multiplying ionizing collisions with gas molecules, resulting in an avalanche of electrons. A significant proportion of the electrons produced in the avalanche exit the multiplication region for collection by the charge collection electrode, or cascaded into a second multiplying region, for further gain (multi-GEM structures). Unlike other gaseous ionization detectors, the detected (negative) signal on the charge collection electrode is produced only by the electrons, rather than also from slower positive ions, making the GEM potentially very fast while reducing space charge effects. Furthermore, the relatively low field gap between the GEM and charge collection electrodes reduces the probability of the propagation of a discharge to the detector electronics.

Thick GEMs (THGEMs), having thicknesses of typically 0.5 mm to 2 mm, are desirable for large area detectors, being structurally self-supporting and hence affording control of spacing between adjacent stacked electrodes.

Manufacturing of GEMs by etching is limited to only materials that may be suitably etched, such as Kapton. In contrast, manufacturing of THGEMs may be by mechanically drilling, using a cutter, the holes therethrough. For example, a conventional THGEM may be manufactured by costly individually mechanically drilling more than 200,000 holes, having a diameter of 400 μm, through a FR4 (glass-reinforced epoxy laminate material) substrate. The drilling limits the smoothness of walls of the drilled holes, the substrate that may be used and quality control, particularly in view of the number of holes to be drilled. These limitations adversely affect the gain, stability and/or uniformity of the THGEM.

Hence, there is a need to improve manufacturing of GEMs, for example THGEMs.

Summary of the Invention

It is one aim of the present invention, amongst others, to provide a method of manufacturing a GEM and a GEM which at least partially obviates or mitigates at least some of the disadvantages of the prior art, whether identified herein or elsewhere.

A first aspect provides a method of manufacturing, at least in part, a gas electron multiplier, GEM, the method comprising:

providing a precursor, comprising a substrate, for example a sheet or a plate, having opposed first and second surfaces;

masking the first surface of the precursor using a first mask defining a first set of apertures, including a first aperture, at least partly therethrough; and

perforating the masked precursor, thereby forming a set of perforations, including a first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures;

wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures.

A second aspect provides a gas electron multiplier, GEM, preferably a thick GEM, THGEM, the GEM comprising:

a substrate having a first conductive layer thereupon, for example a sheet or a plate, having opposed first and second surfaces, having a set of perforations, including a first perforation, therethrough;

wherein the substrate comprises and/or is glass and/or a ceramic; and

optionally, wherein the first conductive layer comprises and/or is a conductive oxide.

A third aspect provides a detector comprising a set of GEMs, including a first GEM, manufactured according to the first aspect and/or according to the second aspect.

Detailed Description of the Invention

According to the present invention there is provided a method of manufacturing a gas electron multiplier, as set forth in the appended claims. Also provided is a gas electron multiplier and a detector comprising a gas electron multiplier. Other features of the invention will be apparent from the dependent claims, and the description that follows.

Method of manufacturing a gas electron multiplier

The first aspect provides a method of manufacturing, at least in part, a gas electron multiplier, GEM, the method comprising:

providing a precursor, comprising a substrate, for example a sheet or a plate, having opposed first and second surfaces;

masking the first surface of the precursor using a first mask defining a first set of apertures, including a first aperture, at least partly therethrough; and

perforating the masked precursor, thereby forming a set of perforations, including a first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures;

wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures.

In this way, the perforations are formed at least partly through the precursor of the GEM by eroding (i.e. by abrading) the precursor where the precursor is exposed by the first set of apertures defined in the first mask. In this way, the set of perforations may be formed in materials (i.e. of the precursor) that are not amenable (for example unsuitable, complex and/or costly) to conventional manufacturing processes, such as chemical etching or mechanical drilling, thereby providing improved properties, for example mechanical and/or electrical, for the GEM. That is, range of materials from which the GEM is manufactured is increased, thereby allowing better selection of an appropriate material based on requirements of the GEM rather than limitations of the conventional manufacturing processes. Additionally and/or alternatively, the set of perforations may be formed having desirable shapes and/or dimensions in the precursor, that may not be formed by conventional manufacturing processes, thereby enhancing performance of the GEM. Additionally and/or alternatively, surfaces of the set of perforations may be improved compared with perforations formed by conventional manufacturing processes, thereby enhancing performance of the GEM.

GEM

The first aspect provides the method of manufacturing, at least in part, a gas electron multiplier, GEM.

It should be understood that the method of manufacturing according to the first aspect may thus provide at least some of the steps required to manufacture the GEM though may include other steps, as understood by the skilled person. Particularly, the method of manufacturing according to the first aspect is directed towards forming the set of perforations through the precursor.

GEMs are known. See, for example, https://kt.cern/technologies/gas-electron-multiplier, WO1999/021211, WO/2003/055288 and WO/2010/091695, which are incorporated herein by reference in entirety.

Precursor

The method comprises providing the precursor, comprising the substrate, for example a sheet or a plate, having opposed first and second surfaces.

In one example, the precursor consists of the substrate. For example, the precursor may be an uncoated sheet of glass, as described below. In one example, the precursor comprises an uncoated substrate. That is, a composition of the first and/or second surface of the substrate a substantially similar to the bulk substrate, notwithstanding that the substrate may comprise a composite material. Hence, the method of manufacturing according to the first aspect may use an uncoated substrate.

If the precursor consists of the substrate, the electrode(s) of the GEM may be provided on the first and/or second surface of the substrate after forming the set of perforations therethrough. In one example, the method comprises depositing, for example by thermal evaporation, a first conductive layer on the first surface of the substrate, after forming the set of perforations, preferably wherein depositing the first conductive layer comprises not depositing the first conductive layer on a surface of the set of perforations. In one example, the method comprises depositing a second conductive layer on the second surface of the substrate, after forming the set of perforations, preferably wherein depositing the first conductive layer comprises not depositing the first conductive layer on a surface of the set of perforations. In one example, the method comprises depositing a first conductive layer on the first surface of the substrate, after forming the set of perforations, preferably wherein depositing the first conductive layer comprises not depositing the first conductive layer on a surface of the set of perforations, and depositing a second conductive layer on the second surface of the substrate, after forming the set of perforations, preferably wherein depositing the first conductive layer comprises not depositing the first conductive layer on a surface of the set of perforations, wherein the

depositing the first conductive layer and the depositing the second conductive layer are simultaneous or successive. By forming the set of perforations in the uncoated substrate, the first surface and/or the second surface must be conductive coated while avoiding coating of surfaces of the formed set of perforations, as required for operation of the GEM. If surfaces of the formed set of perforations are conductively coated, the conductive coating may be removed from such surfaces, for example by laser etching.

In one example, the precursor comprises a coated substrate, for example wherein the first surface is presented by a coating such as a first conductive layer and/or wherein the second surface is presented by a coating such as a second conductive layer. That is, the first conductive layer provides a first electrode of the GEM and/or the second conductive layer provides a second electrode of the GEM. Hence, the method of manufacturing according to the first aspect may use a coated substrate. It should be understood that the conductive layers are electrically conductive, compositions of which are described below.

In one example, providing the precursor comprises depositing a first conductive layer on the substrate, wherein the first surface is presented by the first conductive layer. In one example, providing the precursor comprises depositing a second conductive layer on the substrate, wherein the second surface is presented by the second conductive layer. In one example, providing the precursor comprises depositing a first conductive layer on the substrate, wherein the first surface is presented by the first conductive layer, and depositing a second conductive layer on the substrate, wherein the second surface is presented by the second conductive layer, wherein the depositing the first conductive layer and the depositing the second conductive layer are simultaneous or successive. By forming the set of perforations in the coated substrate, surfaces of the formed set of perforations are thus not coated by a conductive layer, as required for operation of the GEM.

In one example, the method comprises, comprising coating the first surface, optionally with a first conductive layer.

Substrate

The precursor comprises the substrate, for example a sheet or a plate, having opposed first and second surfaces.

Generally, the substrate should be electrically insulating, or at least highly resistive. The substrate material can certainly not be a highly conductive substrate such as metal, but there is some flexibility in terms of exactly how insulating the substrate must be. In some applications, a very highly resistive material may be a better choice than a completely insulating one.

In one example, the substrate has a resistivity in a range from 10^{10} Ωcm to 10^{17} Ωcm, preferably in a range from 10^{11} Ωcm to 10^{16} Ωcm, more preferably in a range from 10^{12} Ωcm to 10^{15} Ωcm. A highly resistive substrate (as opposed to an insulating substrate) may provide benefits in terms of charging up (accumulation of electrons on the insulating surfaces of the GEM) behaviour. Electrons which accumulate on the insulating surfaces of the GEM modify the electric field within each hole. A highly resistive substrate may allow for the dissipation of the accumulated electric charge.

In one example, the substrate comprises and/or is a glass, for example a borosilicate glass or fused quartz (also known as fused silica), a ceramic, for example alumina, macor, sapphire, silicon carbide or steatite, and/or a composite comprising reinforcement fibres, such as carbon fibre, fibreglass and/or Kevlar RTM, and/or particles.

In one example, the glass comprises SiO_2, CeO_2 <0.01 wt.% preferably <0.001 wt.%, Ag_2O <0.05 wt.% preferably <0.01 wt.%, AuO <0.003 wt.% preferably <0.001 wt.% and unavoidable impurities. In one example, the glass comprises B_2O_3 0 – 20 wt.%, Al_2O_3 0 – 10 wt.%, Na_2O 0 – 6 wt.%, K_2O 0 – 6 wt.%, Sb_2O_3 0 – 1 wt.%, ZnO 0 – 3 wt.%, CeO_2 <0.01 wt.% preferably <0.001 wt.%, Ag_2O <0.05 wt.% preferably <0.01 wt.%, AuO <0.003 wt.% preferably <0.001 wt.%, balance SiO_2 and unavoidable impurities.

Borosilicate glass, such as SCHOTT (RTM) Borofloat 33 (RTM) is relatively low cost. Borofloat 33 has a nominal composition B_2O_3 13 wt.%, Al_2O_3 2 wt.%, Na_2O / K_2O 4 wt.%, balance SiO_2 and unavoidable impurities. Fused silica is radiopure, allowing use in experiments which are very sensitive to background radiation. Fused silica typically comprises SiO_2 ≥99.9 wt.%.

In one example, the substrate does not comprise and/or is not a photoetchable glass, for example Schott FOTURAN or Schott FOTURAN II (available from Schott Corporation, Mainz, Germany) or HOYA PEG3 or HOYA PEG3C (available from HOYA Corporation, Tokyo, Japan).

In one example, the substrate has a hardness in a range from 5 to 12 GPa, preferably in a range from 6 to 10 GPa and/or a fracture toughness in a range from 0.1 to 5 $MPam^{0.5}$, preferably in a range from 0.25 to 2.5 $MPam^{0.5}$. In this way, the substrate is relatively hard while amenable to abrading, for example abrasive etching.

In one example, the substrate has a thickness in a range from 0.25 to 5.0 mm, preferably in a range from 0.4 to 2.5 mm, more preferably in a range from 0.75 to 1.5 mm, for example 1.0 mm. By increasing the thickness of the substrate, an area of the GEM can be increased, thereby providing a larger detector.

Conductive layer

In one example, providing the precursor comprises depositing a first conductive layer on the substrate, wherein the first surface is presented by the first conductive layer. In this way, electrodes for the GEM may be provided, for example as described previously.

It should be understood that the first conductive layer comprises and/or is an electrically conductive layer. Typically, electrodes for GEMs comprise and/or are metallic layers, for example copper, such as to provide a metal-clad insulator. As described below, by expanding the range of materials that may be used for the substrate, the range of materials that may be used for the conductive layers may be similarly expanded.

In one example, the first conductive layer comprises and/or is a metal, for example a first row transition metal such as Cu and/or a noble metal such as Ag, Au or Pt, or alloys thereof. Deposition of such metals is known.

In one example, the first conductive layer comprises and/or is a conductive oxide, for example indium tin oxide (ITO), doped zinc oxide such as indium doped zinc oxide (IZO) and/or fluorine doped tin oxide (FTO). Such conductive oxides may be transparent conducting oxides.

In one example, the first conductive layer has a thickness in a range from 1 to 100 μm, preferably in a range from 2.5 to 50 μm, more preferably in a range from 5 to 25 μm. That is, the thickness of the first conductive layer is relatively small compared with that of the substrate.

In one example, depositing the first conductive layer on the substrate comprises patterning the first conductive layer, for example before and/or forming the set of perforations. In this way, tracks and/or electronic components may be provided in the first conductive layer.

For example, the patterning may be used to define how the GEM is connected to external power supplies, etc. For example, the ITO (or other electrode material) may have specific patterning to allow for easier electrical connection and/or to control electric fields proximal and/or at edges of the GEM. For example, the patterning may define a shape of the electrode around each hole to manipulate the electric field within and/or around the edge(s) of each hole, for example at and/or proximal the first surface and/or the second surface.

Masking

The method comprises masking the first surface of the precursor using the first mask defining the first set of apertures, including the first aperture, at least partly therethrough. Generally, a cross-sectional shape of the first perforation corresponds with a cross-sectional shape of the first aperture since the first perforation is formed by abrading therethrough.

It should be understood that the first mask is suitable for abrading through the first set of apertures thereof. Typically, such masks comprise a resilient material, for example a photoresist laminate as described in US4764449A, US20020115014A1 and US5415971A, the subject matter of which is incorporated herein by reference in their entirety. In one example, masking the first surface of the precursor comprises applying a photoresist thereon and providing the first mask defining the first set of pictures using photolithography.

In one example, a cross-sectional shape of the first aperture is a circle or a polygon, for example a regular polygon such as an equilateral triangle, a square, a hexagon, an octagon, etc. Other cross-sectional shapes may be provided. In one example, the first set of apertures includes M apertures, wherein M is a natural number greater than or equal to 1, for example in a range from 10^0 to 10^9, preferably in a range from 10^2 to 10^8, more preferably in a range from 10^3 to 10^7. In one example, the set of apertures comprises an array of M apertures, preferably a regular array for example a close-packed array. In one example, the respective apertures of the first set thereof are mutually spaced apart, for example mutually equispaced. In one example, the M apertures are as described with respect to the first aperture. In one example, the M apertures are mutually different, for example tailored according to respective positions.

It should be understood that the set of perforations may be formed through the precursor by abrading only via the first set of apertures of the first mask (i.e. single sided). Alternatively, the first set of perforations may be formed through the precursor by abrading from both sides (i.e. double sided) and hence via the first set of apertures of the first mask and via a second set of pictures of a second mask, as described below.

In one example, the method comprises:

masking the second surface of the precursor using a second mask defining a second set of apertures, including a first aperture, at least partly therethrough, wherein the second set of apertures correlates with the first set of apertures; and

wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the second set of apertures.

In one example, the method comprises masking the second surface of the precursor using a second mask defining a second set of apertures, including a first aperture, at least partly therethrough. The second mask may be as described with respect to the first mask. In one example, the method comprises aligning the first set of apertures and the second set of apertures, for example optically, thereby correlating or coinciding the first set of apertures and the second set of apertures. In one example, respective centres of the first set of apertures and the second set of apertures are within 10%, preferably within 5%, more preferably within 2.5%, most preferably within 1% coincidence by a diameter thereof. In this way, the first mask and the second mask may be axially aligned, for example accurately and/or precisely. In one example, the method comprises masking the first surface and masking the second surface before forming the set of perforations. In one example, the method comprises masking the first surface, forming the set of perforations partially through the precursor, masking the second surface and forming the set of perforations fully through the precursor (i.e. double sided abrading).

In other words, the following combinations are possible:

1. Mask from one side, abrade from one side, mask the other side, abrade from the other side;
2. Mask both sides and then abrade both sides, successively or simultaneously.

In one example, the first mask and/or the second mask defines a shape of the GEM, for example an outer perimeter thereof. In this way, the shape of the GEM may be customised simultaneously with forming the set of perforations.

In one example, the method comprises comprising removing the first mask after abrading the masked precursor. Processes to remove the first mask are known.

Perforating

The method comprises perforating the masked precursor, thereby forming the set of perforations, including the first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures.

That is, the set of perforations is formed by abrading the precursor through the first set of apertures. It should be understood that the set of perforations is formed fully through the precursor during single sided abrading. Conversely, it should be understood that the set of perforations is formed partially through the precursor from each side during double sided abrading, so as to form the set of perforations fully through the precursor.

It should be understood that the set of perforations corresponds, at least in part, to the first set of apertures, for example by number, number density, position, cross-sectional shape and/or cross-sectional dimensions.

In one example, a cross-sectional shape of the first perforation is a circle or a polygon, for example a regular polygon such as an equilateral triangle, a square, a hexagon, an octagon, etc. Other cross-sectional shapes may be provided. In one example, the first set of perforations includes N perforations, wherein N is a natural number greater than or equal to 1, for example in a range from 10^0 to 10^9, preferably in a range from 10^2 to 10^8, more preferably in a range from 10^3 to 10^7. In one example, N = M. In one example, the set of perforations comprises an array of N perforations, preferably a regular array for example a close-packed array. In one example, the respective perforations of the first set thereof are mutually spaced apart, for example mutually equispaced. In one example, the N perforations are as described with respect to the first perforation. In one example, the N perforations are mutually different, for example tailored according to respective positions.

The perforations may be as described with respect to the second aspect.

Abrading

Perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures. In this way, the set of perforations is formed by erosion. It should be understood that abrading the masked precursor, for example by abrasive etching, via the first set of apertures generally results in abrading via one or more apertures of the set thereof simultaneously.

In one example, abrading the masked precursor via the first set of apertures comprises abrading the masked precursor by flowing abrasive media theretowards, for example in a fluid carrier such as pneumatically or hydraulically (i.e. abrasive etching), such as from one or more nozzles. In one example, the nozzles are moved, translated, rotated and/or inclined relative to the first surface during the abrading, for example while rastering or spiralling across the first surface. The abrading may be as described in WO2014089224A1, the subject matter of which is incorporated herein by reference in entirety

In one example, abrading the masked precursor via the first set of apertures comprises pneumatically abrading the masked precursor using abrasive media (i.e. abrasive etching), for example silicon carbide and/or aluminium oxide, having a size (for example D50) in a range from 1 μm to 100 μm, preferably in a range from 5 μm to 50 μm, at a pressure in a range from 69 kPa

(10 psi) to 6,900 kPa (1,000 psi), preferably in a range from 275 kPa (40 psi) to 690 kPa (100 psi). Other abrasive media are known. Generally, angular abrasive media are preferred.

In one example, flowing the abrasive media comprises controlling a pressure and/or a flow rate thereof, for example flowing the abrasive media at a relatively lower pressure and/or flow rate initially and flowing the abrasive media at a relatively higher pressure and/or flow rate thereafter. In this way, abrading of the precursor may be at a relatively lower rate initially and at a relatively higher rate thereafter, thereby improving a quality of the set of perforations proximal and/or at the first surface while accelerating forming of the set of perforations. For example, chipping or spalling may be reduced. In one example, controlling the pressure and/or the flow rate of the flowing abrasive media comprises flowing the abrasive media at a relatively lower pressure and/or flow rate finally, thereby improving a quality of the surfaces of the set of perforations by abrading at a relatively lower rate to finish.

In one example, flowing the abrasive media comprises controlling a direction (i.e. orientation with respect to the first surface), for example by adjusting inclination and/or rotation of one or more nozzles. In this way, a taper angle of the set of perforations may be controlled.

In one example, abrading the masked precursor via the first set of apertures comprises repeatedly abrading the masked precursor, for example by multi-pass abrading, as generally described above. In one example, successive passes are at different pressures, flow rates, directions and/or using different abrasive media, thereby optimising forming of the set of perforations, for example to achieve high quality perforations quickly.

In one example, abrading the masked precursor via the first set of apertures comprises uniformly abrading the masked precursor via the first set of apertures, thereby providing uniform (i.e. identical or quasi-identical) perforations. In this way, properties of the GEM are generally constant thereacross.

In one example, abrading the masked precursor via the first set of apertures comprises differentially abrading the masked precursor via the first set of apertures, thereby providing graduated perforations. In this way, properties of the GEM may be tailored thereacross.

Treating

In one example, the method comprises mechanically, thermally and/or chemically treating the perforated precursor, for example to improve mechanical properties of the substrate.

For example, application of a thin (<1.5 micron) amorphous silicon or amorphous silicon oxide layer may provide anti-static properties to the walls of the GEM holes. This is intended to reduce charging up effects. Other coatings such as reflective coatings could also be possible to tailor the optical properties of the GEM holes (increase light output by reflecting light that would otherwise be absorbed by the walls of the holes).

Gas electron multiplier

The second aspect provides a gas electron multiplier, GEM, preferably a thick GEM, THGEM, the GEM comprising:

a substrate having a first conductive layer thereupon, for example a sheet or a plate, having opposed first and second surfaces, having a set of perforations, including a first perforation, therethrough;

wherein the substrate comprises and/or is glass and/or a ceramic; and

optionally, wherein the first conductive layer comprises and/or is a conductive oxide.

The GEM, the substrate, the first conductive layer, the sheet, the plate, the opposed first and set surfaces, the set of perforations, the first perforation, the glass, the ceramic and/or the conductive oxide may be as described with respect to the first aspect.

In one example, the substrate does not comprise and/or is not a photoetchable glass, for example Schott FOTURAN or Schott FOTURAN II (available from Schott Corporation, Mainz, Germany) or HOYA PEG3 or HOYA PEG3C (available from HOYA Corporation, Tokyo, Japan).

In one example, the first perforation has a cross-sectional dimension at the first surface and/or the second surface that is greater than a cross-sectional dimension therebetween. That is, the first perforation tapers away from the first surface and/or the second surface. In contrast, perforations formed by mechanical drilling are cylindrical. As described below, tapering perforations, particularly tapering from both surfaces, maybe advantageous.

In one example, the first perforation comprises and/or is a bifrustoconical or bifrustopyramidal perforation (i.e. hour-glass shaped), for example having substantially conical or planar walls respectively. It should be understood that bifrustoconical and bifrustopyramidal relate to circular and polygonal cross-sectional shapes of the first perforation at the first surface and/or the second surface, respectively. In one example, a taper angle of the first perforation is in a range from 2° to 45°, preferably in a range from 6° to 35°, more preferably in a range from 10° to 15°, for example about 13°, measured orthogonal to the first surface and/or the second surface. In one example, the first perforation comprises and/or is a frustoconical or frustopyramidal perforation. In one example, the first perforation comprises and/or is a cylindrical or polyhedral perforation.

In one example, the first perforation comprises and/or is a bifrustoconical or bifrustopyramidal perforation having a cylindrical or polyhedral perforation portion between opposed frustoconical or frustopyramidal portions, respectively. In one example, the first perforation comprises and/or is a frustoconical or frustopyramidal perforation having no cylindrical or polyhedral perforation portion between opposed bifrustoconical or bifrustopyramidal portions, respectively. In one example, the first perforation comprises and/or is a frustoconical or frustopyramidal perforation comprising a frustoconical or frustopyramidal perforation portion and a cylindrical or polyhedral perforation portion, respectively.

In one example, the first perforation has a cross-sectional dimension (for example diameter, maximum dimension between diametrically opposite sides) at the first surface and/or the second surface in a range from 0.125 mm to 2.5 mm, preferably in a range from 0.2 mm to 1.25 mm, more preferably in a range from 0.375 mm to 0.75 mm, for example 0.5 mm.

In one example, a ratio of a thickness of the substrate to the cross-sectional dimension is in a range from 4 : 1 to 1 : 4, preferably in a range from 3 : 1 to 1 :3, more preferably in a range from 2 : 1 to 1 : 2, for example 1 : 1.

In one example, the first perforation has a circular or polygonal cross-sectional shape at the first surface and/or the second surface, as described previously.

In one example, the set of perforations comprises an array of perforations, preferably a regular array for example a close-packed array, as described previously.

In one example, the GEM has an open area (also known as effective area), provided by the set of perforations at the first surface and/or the second surface, in a range from 30% to 90%, preferably in a range from 60% to 80%, by area of the GEM.

In one example, a number density of the respective perforations of the set thereof is in a range from 1 to 250 mm^{-2}, preferably in a range from 5 to 100 mm^{-2}.

In one example, the GEM has a thickness in a range from 0.25 mm to 5.0 mm, preferably in a range from 0.4 mm to 2.5 mm, more preferably in a range from 0.75 mm to 1.5 mm, for example 1.0 mm.

In one example, the GEM has an area in a range from 0.0001 m^2 to 10.0 m^2, preferably in a range from 0.025 m^2 to 2.5 m^2, preferably in a range from 0.1 m^2 to 1 m^2.

Detector

The third aspect provides a detector comprising a set of GEMs, including a first GEM, manufactured according to the first aspect and/or according to the second aspect.

Definitions

Throughout this specification, the term "comprising" or "comprises" means including the component(s) specified but not to the exclusion of the presence of other components. The term "consisting essentially of" or "consists essentially of" means including the components specified but excluding other components except for materials present as impurities, unavoidable materials present as a result of processes used to provide the components, and components added for a purpose other than achieving the technical effect of the invention, such as colourants, and the like.

The term "consisting of" or "consists of" means including the components specified but excluding other components.

Whenever appropriate, depending upon the context, the use of the term "comprises" or "comprising" may also be taken to include the meaning "consists essentially of" or "consisting essentially of", and also may also be taken to include the meaning "consists of" or "consisting of".

The optional features set out herein may be used either individually or in combination with each other where appropriate and particularly in the combinations as set out in the accompanying claims. The optional features for each aspect or exemplary embodiment of the invention, as set out herein are also applicable to all other aspects or exemplary embodiments of the invention, where appropriate. In other words, the skilled person reading this specification should consider the optional features for each aspect or exemplary embodiment of the invention as interchangeable and combinable between different aspects and exemplary embodiments.

Brief description of the drawings

For a better understanding of the invention, and to show how exemplary embodiments of the same may be brought into effect, reference will be made, by way of example only, to the accompanying diagrammatic Figures, in which:

Figure 1 schematically depicts a method according to an exemplary embodiment;

Figure 2 schematically depicts a method according to an exemplary embodiment, in more detail;

Figure 3 is a photograph of a glass wafer coated with indium tin oxide (ITO) electrode on top and bottom faces (i.e. a substrate), for manufacturing a GEM according to method according to an exemplary embodiment;

Figure 4A is a design of a mask for manufacturing a GEM according to method according to an exemplary embodiment; and Figure 4B schematically depicts an enlargement of the mask, in more detail;

Figure 5A is a photograph of a mask according to Figure 4; Figure 5B is a photograph of the substrate of Figure 3 after film lamination using the mask; Figure 5C is a photograph of optical alignment of top and bottom masks; Figure 5D is a photograph of the masked substrate for abrasive etching;

Figure 6A is a photograph of the GEM manufactured according to an exemplary embodiment; Figure 6B is a photograph of a perforation in the GEM; Figure 6C schematically depicts a through-thickness cross section of the perforation; and Figure 6B is a photograph of a perforation in a GEM;

Figure 7 is a photograph of the GEM of Figure 6A installed in a detector, particularly an ARIADNE Prototype: (a) operating principle and (b) TPC. As a single phase, optical readout GArTPC, a wavelength shifter (TPB) is used to shift the 128 nm VUV S2 scintillation light to 420 nm visible light. This is then imaged with an EMCCD. (c) A Borofloat 33 G-THGEM and (d) conventional copper-coated FR4 PCB THGEM mounted on the ARIADNE prototype TPC.

Figure 8 is a graph of signal intensity as a function of field for GEMs according to exemplary embodiments and for a conventional GEM;

Figure 9A is a graph of summed signal intensity as a function of time for a conventional GEM; and Figure 9B is a graph of summed signal intensity as a function of time for a GEM according to an exemplary embodiment;

Figure 10A is a mask for manufacturing a GEM according to method according to an exemplary embodiment; and Figure 10B schematically depicts an enlargement of the mask, in more detail;

Figure 11 is a photograph of a plurality of perforations in the GEM manufactured using the mask of Figure 10A;

Figure 12 is a visual representation of the novel abrasive machining technique for the production of G-THGEMs, according to an exemplary embodiment;

Figure 13: Hole topographies for (a) circular and (b) hexagonal masks, with the repeat unit overlayed. These masks dictate the hole structure of the G-THGEMs, formed via abrasive machining. The hole sizes and pattern dimensions are given in Table 1.

Figure 14: A cutaway schematic of the hole geometry for the (a) G-THGEM, formed by abrasive machining, and the mechanically drilled holes of a (b) conventional THGEM. The G-THGEM/THGEM substrates are shown in grey, with electrodes represented in black. The G-THGEMs are rimless, with a bi-conical shaped hole, while the THGEM has a 50 µm rim and straight-walled holes.

Figure 15 is an EMCCD image of approximately 30 alpha particle GAr interactions, induced by a 30 kBq ^{241}Am alpha source, collimated to 500 Bq;

Figures 16A and 16B show the charging behaviour, manifesting as variation in S2 light intensity, of the various types of bi-conical hole G-THGEMs and cylindrical hole FR4 THGEM. Figures 16A and 16B represent time binnings of 1 s and 20 s, respectively. All functions in Figure 16B have been fitted using Equation (1), the parameters of which can be found in Table 3. The data colour is consistent with the legend on Figure 8.

Detailed Description of the Drawings

Figure 1 schematically depicts a method according to an exemplary embodiment.

The method is of manufacturing, at least in part, a gas electron multiplier, GEM.

At S101, the method comprises providing a precursor, comprising a substrate, for example a sheet or a plate, having opposed first and second surfaces.

At S102, the method comprises masking the first surface of the precursor using a first mask defining a first set of apertures, including a first aperture, at least partly therethrough.

At S103, the method comprises perforating the masked precursor, thereby forming a set of perforations, including a first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures; wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures.

The method may comprise any of the steps described with respect to the first aspect.

Figure 2 schematically depicts a method according to an exemplary embodiment, in more detail.

S201: Select (glass) substrate and apply electrode coating on top and bottom.
S202: Apply mask to the substrate, obscuring the areas which should not be machined
S203: Using abrasive nozzles, machine one side of the part. Only the areas exposed by the mask are machined.
S204: Repeat the process from the other side.
S205: Mask is removed from both sides, leaving the finished GEM.
S206: Potential is applied across the device and operates as a GEM.

Figure 12 is a visual representation of the novel abrasive machining technique for the production of G-THGEMs, according to an exemplary embodiment. The manufacturing process for G-THGEMs is composed of several distinct steps. A visual representation is shown in Figure 12. First, a substrate is selected. The substrate must generally be nonductile, favouring materials such as glass or ceramics. In this work, fused silica and Schott Borofloat 33 substrates were tested. The exact substrate can be tailored according the requirements of the application. For example, synthetic fused silica can be made especially radiopure and would therefore be ideally suited for experiments requiring low backgrounds. Schott Borofloat 33 is relatively lower cost and may be well suited for applications requiring high resistance to thermal shock. For this investigation, all substrates were selected to be 1 mm thick, identical to that of the traditional FR4 THGEM.

The next step in the manufacturing process is the formation of electrodes. In this work, a vacuum deposited 150 W/Sq indium tin oxide (ITO) coating is applied on both sides of the substrate. A simple mask, as shown in orange in Figure 12, is used during the coating process to define the shape of the electrode—in this case, the electrode area is a 163 mm diameter circle on the 200 mm diameter substrates. A photograph of the substrate with ITO coating is shown in Figure 3. ITO was selected predominantly for its relatively low cost and good availability, although many different electrode materials could be applied. The controllable sheet resistance of the ITO coating may provide additional benefits when compared to highly conductive coatings—this is discussed below. More intricate electrode geometries may also be possible via laser etching of the electrode coating.

The substrate, now with electrodes on both sides, is ready for the through hole machining process. The position and shape of the through holes are defined using a 2D CAD drawing, such as a drawing exchange format (DXF) file. For the best results during the machining process, the

diameter of the holes should typically be at least half of the substrate thickness. For example, for a 1 mm thick substrate, hole diameters ≥0.5 mm are preferred. Figure 13 shows a schematic of two hole layouts which were tested in this work. One design uses the conventional THGEM dimensions: 0.5 mm diameter holes on a hexagonal array with a hole-to-hole pitch of 0.8 mm. The second design resembles a honeycomb structure, with hexagonal holes on a hexagonal array. This design highlights new capabilities provided by the manufacturing process—no longer being limited to geometries which can be produced by drilling.

THGEM Type	Substrate	Electrode	Hole Shape	Hole Size (μm)	Hole Pitch (μm)	Rim Size (μm)
FR4 circ	FR4	Cu	Circle	500	800	50
FS circ	FS	ITO	Circle	500	800	None
BF circ	BF	ITO	Circle	500	800	None
BF hex	BF	ITO	Hexagonal	870	1100	None

Table 1. A summary of the G-THGEM/THGEM types investigated in this paper, including substrates, electrodes, hole pattern, size, shape and rims. The short-hand naming convention represents the G-THGEM/THGEM's substrate and hole shape, where "FS" and "BF" refers to fused silica and Schott Borofloat 33, respectively.

The resulting mask, shown in purple in Figure 1, which defines the location and shape of the through holes, is applied to both sides of the substrate. This mask is patterned via a photolithography technique, selectively producing areas which resist the abrasive machining process. Then, a series of abrasive delivery nozzles traverse the substrate, selectively abrading the substrate in the regions which are not masked. Typical abrasive materials includes aluminium oxide or silicon carbide, with a particle size of around 20–25 μm. When performed from one side, the abrasion process produces holes which taper inwards with increasing depth into the substrate. The taper angle (controllable between 6–35 degrees) was measured to be approximately 12 degrees in this work. Once the process is completed on one side of the substrate, the substrate is flipped and the process is repeated on the other side. By abrading the substrate from both sides, biconical through holes are produced. The outer perimeter of the substrate can also be shaped by this process. In this work, the diameter was reduced to 179 mm. A schematic comparing holes of the G-THGEM to those of traditional FR4 THGEMs is shown in Figure 14. A photograph comparing the G-THGEM and THGEM holes can be seen in Figures 6B and 6D (abrasively machined holes in Borofloat 33 G-THGEM and drilled holes in the FR4 THGEM. Both G-THGEM/THGEM holes are 500 μm in diameter.) Small edge chipping (less than 10 μm) occasionally occurs around the G-THGEM holes from the abrasive machining process. No discernible effects on the behaviour of the G-THGEMs were identified, including discharge behaviour around these holes. Optimisation of the production technique is ongoing, including varying the abrasive media, particulate size and the delivery pressure. The bi-conical shape of G-THGEM holes produces distinctive dielectric charging behaviour during operation—this is discussed further below.

Following the abrasive blasting process, the mask is removed and the final G-THGEM is realised. A photograph of a complete G-THGEM is shown in Figure 6A. For these G-THGEM prototypes, no special cleaning processes were afforded before use. However, multiple types of cleaning could be permitted: for example, the use of an ultrasonic bath. In this work, an electrical connection is made to the top and bottom ITO electrodes using spring-loaded contacts connected to the outer perimeter of the electrode.

Experimental

G-THGEMs

Table 1 summarises the four THGEMs, with their respective combinations of substrate material, electrode coating and hole shape and size. Both the G-THGEMs and FR4 THGEM have a 179 mm diameter, with a 163 mm diameter active area. Two substrate materials were tested for the G-THGEMs: SCHOTT Borofloat 33 and fused silica. Borofloat 33 is relatively low cost, enabling potential large scale production of relatively inexpensive G-THGEMs, whereas fused silica is radiopure, potentially allowing use in experiments which are very sensitive to background radiation (for example, dark matter TPCs).

The abrasive machining process allows for more complex THGEM hole topography than conventional manufacturing methods. To highlight this capability, a G-THGEM with hexagonal holes was also tested. Hexagonal holes can be packed more densely (shown in Figure 3), offering higher open areas and possibly increased electron transparency. The open area of the hexagonal G-THGEM is 62%, compared to 35% of the circular holes. There are several mechanical advantages afforded by G-THGEMs which makes them suitable for large-scale LArTPC experiments. Firstly, both Borofloat 33 and fused silica are stiffer than FR4 and can be produced in large flat surfaces, with thickness variation tolerances typically superior than what is possible for FR4. Large-scale experiments, for example DUNE, utilise PCB substrate LEMs with reported thickness variations approaching 5%, with a rejection rate of less than 1 LEM per charge readout plane (CRP) (18 LEMs). Borofloat 33 sheets are available with thickness variations of ≤15 μm for 1 mm thick substrates, resulting in a thickness variation of less than 1.5%. This is an important consideration in achieving high THGEM gain uniformity. Differential surface flatness and THGEM bowing both contribute to THGEM field distortions. SCHOTT Borofloat 33 and fused silica are reported with flexural moduli of 64 GPa and 72 GPa, respectively. The flexural strength of epoxy laminate/FR4 used to produce THGEMs does not typically exceed 23 GPa (crosswise). Glass is less porous than FR4, making it less susceptible to contamination. This presents obvious advantages to detectors with high purity requirements. A common type of G10/FR4 is Textolite G 10 FR4, manufactured by General Electric, and this

has been reported to have a total mass loss (TML) and collected volatile condensable material (CVCM) outgassing rate of 0.44% and 0.01%, respectively [33]. Silica-based glasses/ceramics such as borosilicate (Borofloat), fused silica or aluminium silicate typically have relatively lower outgassing rates.

ARIADNE Prototype TPC

Each of the four G-THGEMs/THGEM were characterised using the ARIADNE prototype detector. The ARIADNE prototype, shown in Figure 7, is an optical readout, 40 L cylindrical TPC, with both dual-phase cryogenic and gas capabilities. Characterisation of all THGEMs was undertaken in GAr conditions. The TPC field cage, comprised of 22 stainless steel rings, has a 178 mm diameter with a 20 cm drift length. The field cage is bounded by a cathode grid at the bottom of the TPC and capped at the top with the bottom electrode of the THGEM. The drift field is established between the cathode and bottom THGEM electrode. Outside the TPC active region, mounted on a rotatory feedthrough, is an Americium-241 alpha source, with an initial 30 kBq rate. This is collimated to around 500 Bq. The rotary feedthrough allows the source to be rotated in/out of the TPC volume during operation.

A sheet of tetraphenyl butadiene (TPB)-coated wavelength shifting (WLS) acrylic is mounted directly above the THGEM. This WLS plate shifts the VUV S2 scintillation light from 128 nm [35] to 420 nm. This wavelength is in the high quantum efficiency range of the externally mounted Andor iXon Ultra 888 EMCCD camera. The Andor iXon Ultra 888 EMCCD camera is positioned externally to the detector, at a distance of approximately 600 mm from the THGEM. The EMCCD is combined with a Spacecom VF50095M lens, with a speed of f/0.95 and a focal length of 50 mm, giving a field of view of approximately 160x160 mm^2. The S2 scintillation light is imaged through a 90 mm diameter borosilicate glass viewport. The transparency of the viewport is >90% at 420 nm (the peak of the TPB emission spectrum). The camera is mounted on an adjustable tripod frame which sits on the optical viewport. It was important to maintain consistent field of view and focusing between studies. This was achieved through reinforcement of the legs with locking nuts and retaining EMCCD orientation during reassembly. An 8-inch, TPB coated, Hamamatsu R5912-20-MOD Photomultipler Tube (PMT) is mounted below the TPC. The spectral response range of the PMT lies between 300 and 650 nm, with a quantum efficiency of approximately 30% at 420 nm. Figure 7 shows the ARIADNE prototype TPC, with a Borofloat G-THGEM and a conventional FR4 THGEM mounted.

TPC Operation Principle

The operating principle of the optical readout and ARIADNE prototype TPC in Gar conditions is shown on the left of Figure 7. All G-THGEM/THGEM behaviours were characterised by

monitoring the intensity of the S2 light produced in the THGEM holes. The primary scintillation/ionisation was induced by alpha particle/GAr interactions. The emitted S2 light was imaged with the EMCCD. An emitted alpha particle enters the TPC active region and interacts with GAr, resulting in the emission of prompt scintillation light (S1) and the creation of free electrons by ionisation. The S1 light is detected by the PMT at the bottom of the detector and is used for τ_2 purity monitoring, which is further discussed below.

Free ionisation electrons drift upwards in response to a uniform electric field applied between the cathode and the grounded G-THGEM/THGEM bottom electrode. When electrons reach the top of the field cage, they enter the G-THGEM/THGEM holes. Each electron is then accelerated by the high electric field applied across the THGEM, between bottom and top electrodes. At sufficiently high fields, this acceleration causes the electron to further ionise the GAr, resulting in a Townsend discharge. This exponentially increases the number of electrons. In addition, this process also produces secondary scintillation light—the S2 light signal, through the excitation of GAr atoms. Depending on the applied field, on the order of 100s of photons are produced per accelerated electron. The EMCCD camera images this S2 light, which has been wavelength shifted using TPB to the high quantum efficiency range of the camera.

Experimental Procedure

The TPC chamber was evacuated over 24 h, down to rough vacuum of 10^{-3} mbar. The chamber was then filled to 1100 mbar with N6.0 GAr (99.9999% pure). GAr was continuously flushed through the detector volume, at flow rate of approximately 5 L/min for the duration of the THGEM studies, mitigating any outgassing effects that would otherwise degrade purity. Purity, measured using the slow scintillation component - τ_2 lifetime - was monitored throughout, as described below.

EMCCD camera settings were kept consistent throughout the duration of the experiment—operating with 4 × 4 binning, in full frame mode, with an exposure time of 50 ms. The EMCCD gain value was set to its maximum value of 1000. In this configuration, the EMCCDs had a readout rate of 15 Hz. This rate resulted in approximately 30 alpha GAr interactions recorded in a single image. The cameras were air cooled to less than -60 Celsius before recording to minimise sensor noise.

The TPC drift field was established between the cathode, operated at a bias of -2.5 kV, and the G-THGEM/THGEM bottom electrode, which was grounded. All field shaping rings were connected with a 100 MW resistor chain. The THGEMs were left unbiased and grounded for a 24 h period (in order to be fully discharged) before measurements were taken. Characterisation began with a study into the dielectric charging behaviour of the G-THGEMs/THGEM. During

measurements, biases were applied to the detector in a consistent manner. First, the cathode bias was applied, establishing the drift field. Next, the EMCCD was set to record data. Once the EMCCD had begun recording data, the THGEMs top electrode was biased to near their pre-established breakdown voltage (see Table 2). This pre-established breakdown voltage was determined experimentally before the 24 h discharge period, by slowly increasing the top electrode bias until THGEM discharges occurred.

Charging was investigated, through imaging alpha GAr interactions, over a 30 min window. Care was taken to ensure that the position of the alpha source within the TPC was consistent between runs. By studying the S2 light intensity variation over time, the dielectric charging behaviour of the THGEM can be inferred. After this 30 min charging period, a THGEM bias scan characterisation study was undertaken.

The THGEM bias was reduced from near its predetermined breakdown voltage in 50 V intervals down to 1000 V (at this point, the alpha tracks are barely discernible from the EMCCD sensor noise). For each THGEM bias, 2000 EMCCD images were recorded. Investigation of THGEM charging behaviour before the characterisation was a deliberate choice in order to maximally charge each THGEM before bias characterisation. The results of both experiments are detailed below.

THGEM Type	Charging Study Bias (kV)	Breakdown Voltage (kV)
FR4 circ	1.60	1.80
FS circ	1.60	1.90
BF circ	1.60	1.85
BF hex	1.70	1.80

Table 2. A Table of the THGEM bias during the charging test and the measured breakdown voltage, in 1100 mbar N6.0, flowing at a rate of 5 L/min. The naming convention in the THGEM type is consistent with Table 1.

GAr Purity Monitoring

Purity was monitored using the well-established τ_2 lifetime method. Argon S1 VUV scintillation occurs through two decay paths: (singlet excimer) τ_1 and (triplet excimer) τ_2, the fast and slow component, respectively. As the τ_2 decay time increases with argon purity, this value can be used as a relative purity monitor. It was important to ensure similar purity conditions for each G-THGEM/THGEM study as electronegative impurities, within GAr, could potentially vary the charge gain and S2 scintillation light production.

The highest values of τ_2 lifetime reported for GAr are 3200 ± 300 ns (with variation depending on fitting models) and more recently 3480 ± 65 ns. The PMT at the base of the TPC was used for all purity measurements. Purity measurements were taken after the initial fill of N6.0 GAr, and subsequent measurements were taken while argon was continually flushed through the detector. Data collection began only once τ_2 exceeded 2000 ns (which approximately corresponds to N6.0 argon gas). A final τ_2 lifetime measurement was taken at the end of each THGEM study to validate that purity had been maintained throughout.

Figure 3 is a photograph of a glass wafer coated with indium tin oxide (ITO) electrode on top and bottom faces (i.e. a precursor 11), for manufacturing a GEM according to method according to an exemplary embodiment.

Regions of the glass wafer which should be electrically active in the completed GEM are coated with an electrode material. This coating is performed by an external supplier by providing a drawing showing the areas of the water which should be coated (central region) and which areas should be masked (edges).

In more detail, Figure 3 shows a photograph of a 200mm diameter glass precursor, to produce a 179 mm diameter GEM, coated on top and bottom faces with indium tin oxide (ITO) electrode. ITO is an optically transparent electrode coating that is relatively low-cost. The choice of electrode material can be customised depending on the application. It was found that the sheet resistance provided by the ITO coating provided electrical advantages which are discussed herein. The precursor 11 (and GEM) has a thickness of 1 mm.

The substrate (i.e. glass wafer) is purchased with geometry close to the final desired GEM shape. For example, to produce the 179 mm diameter GEM, a glass wafer with 200mm diameter is provided. The blasting process is able to remove the excess in diameter at the same time as forming the holes. Glass with the finished diameter can also be provided, in case that a specific edge finish is required on the edge of the glass which cannot be produced by blasting.

Figure 4A is a design of a mask M for manufacturing a GEM according to method according to an exemplary embodiment; and Figure 4B schematically depicts an enlargement of the mask M, in more detail.

The mask M defines the shape, size and location of the holes in the wafer and is typically designed in a 2D format such as DXF file. This design defines both the placement and shape of the holes which will be produced. This design defines the areas of the wafer which will be blasted and the areas which will be masked. Figure 4A shows a design for the mask M having circular

holes. The shape of the holes produced in the final GEM are defined by this mask design and the designer may customise the hole shape, spacing, layout, etc to meet specific needs.

Figure 5A is a photograph of a mask M1, generally as described with respect to the mask M according to Figure 4A; Figure 5B is a photograph of the substrate of Figure 3 after film lamination using the mask M1; Figure 5C is a photograph of optical alignment of top and bottom masks M1; Figure 5D is a photograph of the masked substrate for abrasive etching.

Generally, the process comprises:

• A mask is produced according the 2D drawings created in stage 3. This mask could possibly be a photoresist laminate as described in US4764449A, US20020115014A1 or US5415971A.

• The mask is applied to the substrate. This mask partially obscures the substrate, defining the areas which will be blasted and those which will not be blasted. It is believed that both top and bottoms masks are applied before any blasting is performed. Alignment of the masks on the top and bottom surfaces is performed manually, optically.

• A system of at least two abrasive delivery nozzles, configured to direct abrasive material at the substrate move across the substrate, producing the holes. The nozzles may rotate, and move up/down away/towards the substrate as described in WO2014089224A1. The arrangement and movement of these nozzles defines the shape/angle of the walls of the holes that are produced.

Different abrasive etching conditions, in terms of nozzle pressure, abrasive media and abrasive size, have been trialled to optimise the quality of the final holes produced. The best results so far have been achieved using 20 µm SC (silicon carbide) abrasive, as shown in Figure 6B. The blasting was performed in multiple passes and varying pressure, particularly using two passes at 45 PSI and five passes at 80 PSI. Further testing of a smaller grit size (10 µm & 17.5 µm instead of 20 µm) is planned, together with trialling of AO (aluminium oxide). It is conceivable that a variation in all of the number of passes, the pressure for each pass, the type of grit used and the size of the grit used will all contribute to variations in final quality of hole.

• After one side of the substrate has been processed, the substrate is turned over, and the blasting process is repeated on the other side of the substrate.

• The masks are removed.

Figure 6A is a photograph of the GEM 10 manufactured according to an exemplary embodiment; Figure 6B is a photograph of a perforation 100A in the GEM 10; and Figure 6C schematically

depicts a through-thickness cross section of the perforation 100A. Perforations 100B to 100E are also shown, at least in part.

The hole (i.e. perforation 100A) has a cross-sectional dimension at the first surface S1 and the second surface S2, about 500 μm, that is greater than a cross-sectional dimension therebetween, about 275 μm at the midthickness. In this example, the first perforation 100A is a bifrustoconical perforation having no cylindrical perforation portion between opposed frustoconical portions, respectively. Microscope images were used to estimate the taper angle along the walls of the bifrustoconical holes. This taper angle may be tailored to vary the shape (inner/midplane diameter) of the hole. The taper angle of the hole can be tailored depending on blasting setup. The taper angle is estimated to be approximately 13°. This taper angle is adjustable by adjusting blasting process settings. Different taper angles will produce THGEMs with different properties.

Figure 7 is a photograph of the GEM 10 of Figure 6A installed in a detector 1.

Electrical connections are made to the top and bottom electrode surfaces of the GEM 10. The electrode surfaces allow a potential difference to be applied across the substrate in order to operate the device as a GEM.

GEMs according to exemplary embodiments and conventional GEMs were tested within a gas argon Time Projection Chamber (TPC). The argon gas was ionised by an ^{241}Am source and the induced secondary scintillation light (S2) produced within the THGEM holes was captured by an EMCCD camera. 1 second image exposures of the S2 light were recorded at various THGEM electric fields and the performance of different types of THGEMs was compared. This methodology is described in arxiv https://arxiv.org/pdf/1401.0525.pdf.

THGEM characteristics

Figure 15 shows an example of alpha particle interactions with GAr, as captured by the EMCCD. This image has been processed, with a background subtraction removing intrinsic sensor noise. The background image was generated from data taken when the THGEM was fully discharged and unbiased. Subsequently, a Region Of Interest (ROI) cut was made which contains all of the alpha source S2 tracks—this ROI is highlighted in red in Figure 15.

Dielectric Charging Behaviour

For each image, as detailed in Figure 15, the pixel intensities inside the ROI were summed. These summations were then binned into 1 s intervals shown in Figure 16A and also 20 s

intervals shown in Figure 16B. The shorter 1 s intervals better show gain fluctuations throughout the THGEM charging process, whereas the longer 20 s intervals provide improved clarity for charging behaviour and shape.

Figure 15 is an EMCCD image of approximately 30 alpha particle GAr interactions, induced by a 30 kBq ^{241}Am alpha source, collimated to 500 Bq. The EMCCD was configured in 4 × 4 binning, with a 50 ms exposure, and a gain of 1000. This was a direct image taken of the WLS S2 light produced within a fused silica substrate G-THGEM holes, at a field of 1600 V/mm. This image has been background subtracted. The red overlay is an ROI cut for analysis.

Particularly, Figure 15 shows an example of alpha particle interactions with GAr, as captured by the EMCCD. This image has been processed, with a background subtraction removing intrinsic sensor noise. The background image was generated from data taken when the THGEM was fully discharged and unbiased. Subsequently, a Region Of Interest (ROI) cut was made which contains all of the alpha source S2 tracks—this ROI is highlighted in red in Figure 15.

For each image, as detailed in Figure 15, the pixel intensities inside the ROI were summed. These summations were then binned into 1 s intervals shown in Figure 16A and also 20 s intervals shown in Figure 16B. The shorter 1 s intervals better show gain fluctuations throughout the THGEM charging process, whereas the longer 20 s intervals provide improved clarity for charging behaviour and shape.

The most apparent difference in charging behaviour between the G-THGEMs and the traditional FR4 THGEM is that the S2 light intensity of G-THGEMs increases over time, whereas the S2 light intensity of the conventional THGEM decreases over time. The distinct charging behaviours may be explained by differences in hole geometry. As a consequence of the abrasive machining process, G-THGEMs have bi-conical holes. The effect of biconical holes on dielectric charging behaviour is well understood for GEMs, and the theory can be extended to G-THGEMs. The insulating glass substrate provides a surface on which electrons may accumulate over time. Consequently, this accumulated charge will distort the electric field within the G-THGEM hole. In the case of bi-conical holes, this accumulated charge causes an increase in electric field within the exit side of the hole (closer to the top electrode). This results in an increase in gain and therefore increased light production. In contrast, THGEM holes with straight walls exhibit dielectric charging effects which result in the decrease of THGEM gain (and S2 light intensity) over time. This is primarily explained by a differential charge distribution along the walls of the holes.

Despite similar bi-conical hole geometries, clear differences in dielectric charging behaviours are discernible between all G-THGEMs. The Borofloat 33 substrate G-THGEMs, with both

circular and hexagonal hole geometries, had similar S2 light production at T_0. Additionally, both hole layouts resulted in maximal charging time after around 10 mins. This is quantitatively reinforced by their p_0 and p_2 parameters of 2.07 × 10^9 and 0.149 (circular) and 1.49 × 10^9 and 0.162 (hexagonal), respectively. However, the larger hexagonal holes result in around half the light production in a maximally charged state than for the circular holes. The ratio of p_1 values dictates the relative total S2 light production differences at maximal charging. Between circular and hexagonal hole layout, Borofloat 33 G-THGEMs, the p_1 ratio is 1.8. The reduction in S2 light intensity of the hexagonal hole G-THGEM can be attributed to a reduced field for larger holes at the same bias.

Although both the fused silica and Borofloat 33 G-THGEMs have the same circular bi-conical hole geometries, a significant difference of the dielectric charging behaviour can be noticed in Figures 16A and 16B. The ratio of the charging rate parameters, described by p_2, between fused silica and Borofloat 33 is 0.32, leading to the approximately observed charging rate of a third. The ratio of p_1 amplitude parameters is 5.8, describing the approximately six-fold increase in amplitude after 30 min of charging when comparing fused silica to Borofloat 33. One possible explanation for these dielectric charging behaviour differences is that Borofloat 33 will typically contain many more impurities than fused silica. It is conceivable that these impurities may create a pathway by which electrons on the surface of the holes can move, thereby reducing the dielectric charging effect.

All datasets shown in Figure 106B are fitted with Equation (1), where G is the total light intensity per 20 s. The parameters of Equation (1) can be found in Table 3. The parameter p_0 is the initial gain at time T_0. The direction and amplitude of charging are governed by p_1, where a negative (positive) p_1 value represents charging up (down) or, more specifically, greater (less) S2 light production over time. The rate of charging is dictated by parameter p_2.

$$G = p_0 + p_1 e^{-t/p_2} \qquad \text{Equation (1)}$$

THGEM Type	p_0	p_1	p_2
FR4 circ	$1.30 \times 10^9 \pm 1.26 \times 10^6$	$6.60 \times 10^8 \pm 1.42 \times 10^7$	0.782 ± 0.0210
FS circ	$1.02 \times 10^{10} \pm 2.36 \times 10^7$	$-7.48 \times 10^8 \pm 4.12 \times 10^7$	0.04808 ± 0.00560
BF circ	$2.07 \times 10^9 \pm 6.63 \times 10^6$	$-1.30 \times 10^9 \pm 1.23 \times 10^7$	0.149 ± 0.00346
BF hex	$1.49 \times 10^9 \pm 3.05 \times 10^6$	$-7.42 \times 10^8 \pm 6.81 \times 10^6$	0.162 ± 0.00312

Table 3: A Table of the fit parameters for Equation (1), describing the fits in Figure 16B.

Despite similar bi-conical hole geometries, clear differences in dielectric charging behaviours are discernible between all G-THGEMs. The Borofloat 33 substrate G-THGEMs, with both circular and hexagonal hole geometries, had similar S2 light production at T0. Additionally, both hole layouts resulted in maximal charging time after around 10 mins. This is quantitatively

reinforced by their p_0 and p_2 parameters of 2.07 × 10^9 and 0.149 (circular) and 1.49 × 10^9 and 0.162 (hexagonal), respectively. However, the larger hexagonal holes result in around half the light production in a maximally charged state than for the circular holes. The ratio of p_1 values dictates the relative total S2 light production differences at maximal charging. Between circular and hexagonal hole layout, Borofloat 33 G-THGEMs, the p_1 ratio is 1.8. The reduction in S2 light intensity of the hexagonal hole G-THGEM can be attributed to a reduced field for larger holes at the same bias.

Figure 8 is a graph of signal intensity as a function of field for GEMs according to exemplary embodiments and for a conventional GEM. In more detail, Figure 8 shows FR4 THGEM and G-THGEM characterisation plots showing the total light intensity, at a variety of THGEM fields, for 2000 EMCCD images, each containing approximately 30 alpha tracks. All functions have been fitted with Equation (2). The parameters of the fits can be seen in Table 4.

$$I = p_0 x(1 + p_1 e^{p_2 x}) + p_3 \qquad \text{Equation (2)}$$

THGEM Type	p_0	p_1	p_2	p_3
FR4 circ	29.7 ± 8.0	$2.30 \times 10^{-2} \pm 6.3 \times 10^{-3}$	$5.36 \times 10^{-3} \pm 2.1 \times 10^{-4}$	$-7.68 \times 10^4 \pm 1.831 \times 10^5$
FS circ	117 ± 57	$5.50 \times 10^{-4} \pm 2.47 \times 10^{-4}$	$7.78 \times 10^{-3} \pm 3.5 \times 10^{-4}$	$2.97 \times 10^4 \pm 8.32 \times 10^4$
BF circ	$7.15 \times 10^{-3} \pm 3.59 \times 10^{-3}$	$1.85 \pm 3 \times 10^{-3}$	$8.05 \times 10^{-3} \pm 3.0 \times 10^{-4}$	$9.38 \times 10^4 \pm 2.21 \times 10^4$
BF hex	8.37 ± 5.97	$2.35 \times 10^{-2} \pm 1.69 \times 10^{-2}$	$5.76 \times 10^{-3} \pm 4.0 \times 10^{-4}$	$3.49 \times 10^5 \pm 1.39 \times 10^5$

Table 4: A table of fit parameters for Equation (2), describing the fits in Figure 8.

In more detail, exemplary glass GEM devices were compared against a conventional THGEM produced using printed circuit board technology (FR4 substrate instead of glass). The electrodes of a conventional THGEM are made from copper. The holes of a traditional THGEM are formed using mechanical drilling.

S2 Light Production THGEM Bias Scan

A THGEM bias scan study was also performed, detailing the S2 light intensity as a function of the THGEM field. Similar to the method described for the dielectric charging behaviour, an ROI cut was taken around the alpha particles. This was done for all of the 2000 (background subtracted) EMCCD images collected for each THGEM type at a given bias. For each event, within this ROI, the pixel intensities were summed and a distribution produced of the total light intensity, in ADU, for the respective G-THGEMs/THGEM fields. The results of the study are shown in Figure 8.

Nominal THGEM behaviour can be seen for both the G-THGEMs and the FR4 THGEM. At a low field (below approximately 1000V), the THGEMs are in the linear gain regime, and the S2 light

production is purely via electroluminescence. As the field increases, the THGEM enters the electron multiplication regime, and the S2 light intensity is dominated by exponential effects. The overall THGEM S2 light production behaviour can be described by Equation (2) (a convolution of both linear and exponential regimes). The fit parameters for Equation (2), describing the data sets in Figure 8, can be seen in Table 4.

By far, the greatest light intensity comes from the fused silica G-THGEM. Both Borofloat 33 and fused silica G-THGEMs, which have hole sizes comparable to the FR4, produce increased S2 light intensity relative to the FR4 THGEM. This can be attributed to the distinct charging characteristics of the G-THGEMs. The Borofloat 33 G-THGEM with a hexagonal hole pattern produces the least S2 light intensity. This can be attributed to a larger hole, meaning that for the same bias, the electric field within the hole is lower, therefore resulting in relatively less gain and thus reduced S2 light intensity.

Both fused silica and Borofloat 33 G-THGEMs were found to be more resilient to damage than FR4, where irreparable carbonisation can occur after repeated discharges. As noted previously, carbonisation has the potential to severely degrade the performance of the THGEM. Nominally, the highly conducting copper electrode of classical THGEMs can allow a large current flow during discharges. The resistive nature of the ITO electrode coating of the G-THGEMs may possibly be quenching sparks by limiting current flow.

With regards to G-THGEM applications within TPCs, the benefits of increased S2 light intensity are obvious. Firstly, for the same applied bias, increased light intensity could possibly result in a lowered energy threshold of a TPC. Functioning at a lower bias, while giving comparable light intensity, reduces the possibility of discharges, both directly on the THGEM and on connectors, feedthroughs or cabling. Detector stability is an important consideration for long-term, large-scale experiments.

The electron multiplication performance of the exemplary glass THGEMs was found to operate as expected for this type of device. Three variants were tested: (A) fused silica substrate with circular holes (gold curve); (B) Borofloat 33 substrate with circular holes (red curve); and (C) Borofloat 33 substrate with Hexagonal holes (green curve). The performance of the (D) conventional FR4 THGEM is shown as the blue curve. The signal intensity of the exemplary glass THGEMs (A) to (C) is seen to increase exponentially with increasing potential difference, as expected.

Notably, the gain of the exemplary glass THGEMs (A) to (B) is greater for a given electric field compared with the conventional THGEM (D), allowing the same signal intensity to be achieved

at a lower electric field (reducing likelihood of discharge) or a higher signal intensity at the same electric field (higher performance) as the conventional THGEM.

Compared with conventional THGEMs, several clear advantages are observed:

• During operation, sparks/discharges may occur. The glass substrate was found to be more resilient to damage compared to FR4, which may carbonise with repeated exposure to sparks. Once carbonised, the performance of the THGEM is severely degraded, or the device may fail completely. Increased spark tolerance is advantageous for the long-term stability of the device.

• The sheet resistance of the ITO electrode may further reduce the intensity of sparks that occur. The highly conducting copper electrode layer of traditional THGEMs allows a large current to flow when a discharge occurs, potentially allowing for a more energetic discharge. The resistive nature of the ITO coating limits the current that can flow to the discharge, quenching sparks, limiting their energy and reducing the potential to damage the device.

• The glass substrate can be selected with better flatness and thickness tolerances than is possible with FR4 during the printed circuit board production process. Improved flatness and reduced thickness variations of the device yields better gain uniformity across the device.

• The glass substrate outgasses less compared to FR4, which is highly porous. The porous nature of FR4 also makes it more susceptible to contamination. This means that the glass substrate has advantages in detectors with extremely high purity requirements.

Figure 9A is a graph of summed signal intensity as a function of time for a conventional GEM, particularly a FR4 based THGEM with straight walled holes. Over time, charge accumulating on the FR4 surfaces decreases the electric field inside the hole and leads to reduced performance by decreasing the gain (electron multiplication factor) over time until reaching an equilibrium.

Figure 9B is a graph of summed signal intensity as a function of time for a GEM according to an exemplary embodiment, particularly a glass THGEM having hourglass shaped holes. Charge accumulation on the insulating surfaces of the glass walls tends to increase the gain of the device over time until reaching equilibrium. That is, the hourglass shaped holes produced by the blasting process do not exhibit the charging down behaviour of conventional THGEMs having straight walled holes. Instead, the accumulated charge tends to increase the gain of the device over time.

Figure 10A is a design of a mask M2 for manufacturing a GEM according to method according to an exemplary embodiment, particularly having honeycomb shaped (i.e. hexagonal) holes

(compare with Figure 4A). Figure 10B schematically depicts an enlargement of the mask M2, in more detail (compare with Figure 4B).

Figure 11 is a photograph of a plurality of perforations in a GEM 20 manufactured using the mask of Figure 10A. The perforations 200 are hexagonal in cross section with a side to side width of 870 µm.

Although a preferred embodiment has been shown and described, it will be appreciated by those skilled in the art that various changes and modifications might be made without departing from the scope of the invention, as defined in the appended claims and as described above.

Attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at most some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

CLAIMS

1. A method of manufacturing, at least in part, a gas electron multiplier, GEM, the method comprising:

providing a precursor, comprising a substrate, for example a sheet or a plate, having opposed first and second surfaces;

masking the first surface of the precursor using a first mask defining a first set of apertures, including a first aperture, at least partly therethrough; and

perforating the masked precursor, thereby forming a set of perforations, including a first perforation, at least partly therethrough, wherein the set of perforations corresponds, at least in part, to the first set of apertures;

wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the first set of apertures.

2. The method according to claim 1, comprising:

masking the second surface of the precursor using a second mask defining a second set of apertures, including a first aperture, at least partly therethrough, wherein the second set of apertures correlates with the first set of apertures; and

wherein perforating the masked precursor comprises, at least in part, abrading the masked precursor, for example by abrasive etching, via the second set of apertures.

3. The method according to any previous claim, wherein the substrate comprises and/or is a glass, for example a borosilicate glass or fused quartz, a ceramic and/or a composite comprising reinforcement fibres and/or particles.

4. The method according to claim 3, wherein the substrate has a resistivity in a range from 10^{10} Ωcm to 10^{17} Ωcm.

5. The method according to any previous claim, wherein providing the precursor comprises depositing a first conductive layer on the substrate, wherein the first surface is presented by the first conductive layer.

6. The method according to claim 5, wherein depositing the first conductive layer on the substrate comprises patterning the first conductive layer.

7. The method according to any of claims 5 to 6, wherein the first conductive layer comprises and/or is a conductive oxide, for example ITO, IZO, FTO.

8. The method according to any previous claim, comprising removing the first mask after abrading the masked precursor.

9. The method according to claim 8, comprising coating the first surface, optionally with a first conductive layer.

10. The method according to any previous claim, wherein abrading the masked precursor via the first set of apertures comprises pneumatically abrading the masked precursor using abrasive media, for example silicon carbide and/or aluminium oxide, having a size in a range from 5 μm to 50 μm, at a pressure in a range from 275 kPa (40 psi) to 690 kPa (100 psi).

11. The method according to any previous claim, comprising mechanically, thermally and/or chemically treating the perforated precursor.

12. A gas electron multiplier, GEM, preferably a thick GEM, THGEM, the GEM comprising:
a substrate having a first conductive layer thereupon, for example a sheet or a plate, having opposed first and second surfaces, having a set of perforations, including a first perforation, therethrough;
wherein the substrate comprises and/or is glass and/or a ceramic; and
optionally, wherein the first conductive layer comprises and/or is a conductive oxide.

13. The GEM according to claim 12, wherein the first perforation has a cross-sectional dimension at the first surface and/or the second surface that is greater than a cross-sectional dimension therebetween.

14. The GEM according to claim 13, wherein the first perforation comprises and/or is a bifrustoconical perforation.

15. The GEM according to any of claims 12 to 14, wherein the first perforation has a cross-sectional dimension at the first surface and/or the second surface in a range from 0.125 mm to 2.5 mm, preferably in a range from 0.2 mm to 1.25 mm, more preferably in a range from 0.375 mm to 0.75 mm, for example 0.5 mm.

16. The GEM according to any of claims 12 to 15, wherein the first perforation has a circular or polygonal cross-sectional shape at the first surface and/or the second surface.

17. The GEM according to any of claims 12 to 16, wherein the set of perforations comprises an array of perforations, preferably a regular array for example a close-packed array.

18. The GEM according to any of claims 12 to 17, having an open area, provided by the set of perforations at the first surface and/or the second surface, in a range from 30% to 90%, preferably in a range from 60% to 80%, by area of the GEM.

19. The GEM according to any of claims 12 to 18, having a thickness in a range from 0.25 mm to 5.0 mm, preferably in a range from 0.4 mm to 2.5 mm, more preferably in a range from 0.75 mm to 1.5 mm, for example 1.0 mm.

20. The GEM according to any of claims 12 to 19, having an area in a range from 0.0001 m^2 to 10.0 m^2, preferably in a range from 0.025 m^2 to 2.5 m^2, preferably in a range from 0.1 m^2 to 1 m^2.

21. A detector comprising a set of GEMs, including a first GEM, manufactured according to any of claims according to any of claims 1 to 11 and/or according to any of claims 1 to 20.

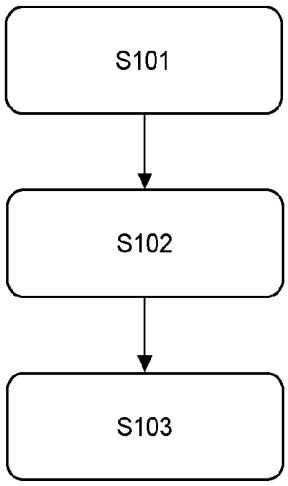


Fig. 1

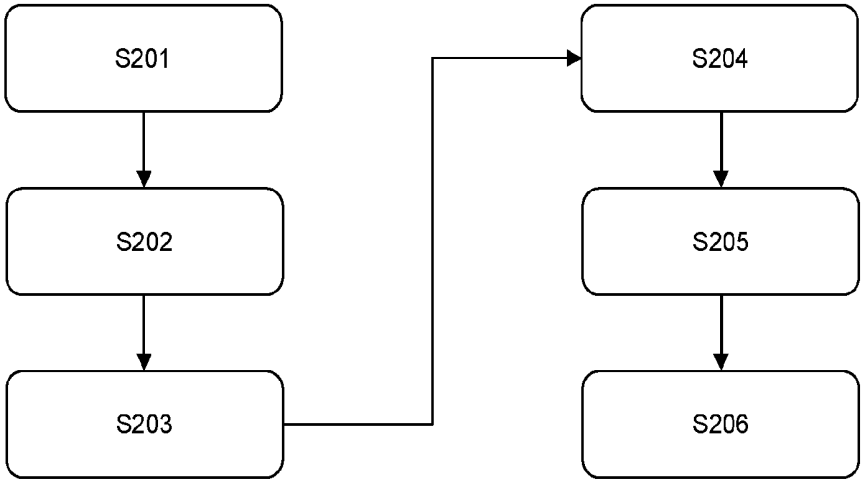


Fig. 2

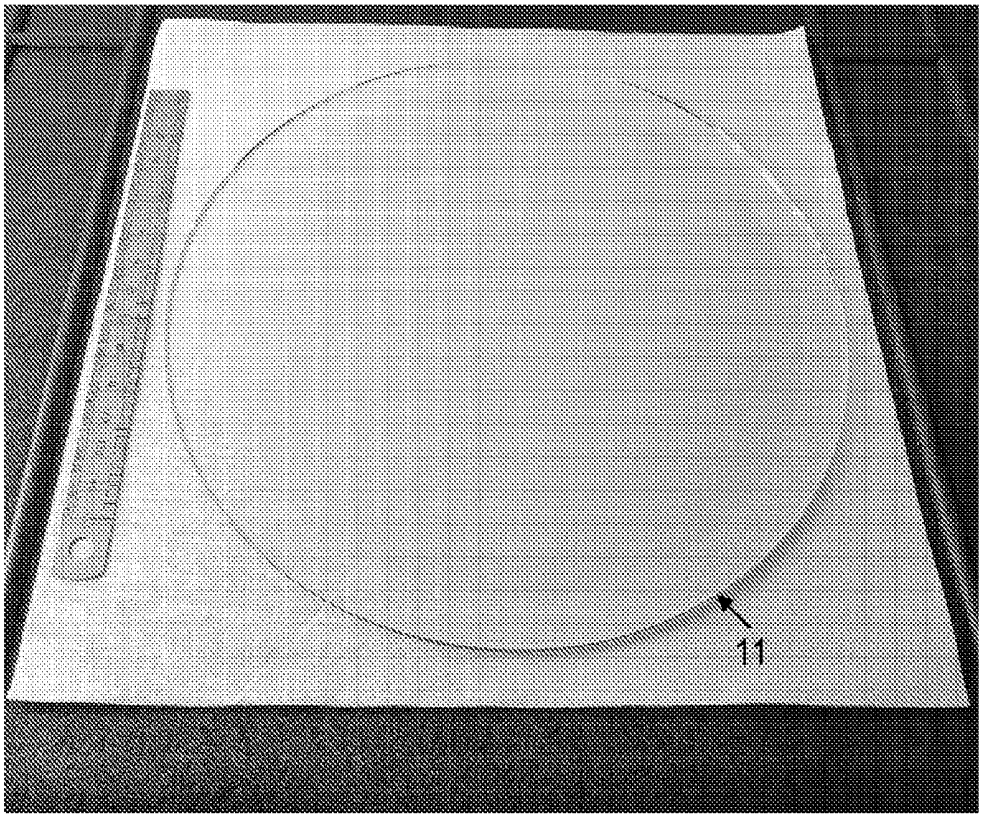


Fig. 3

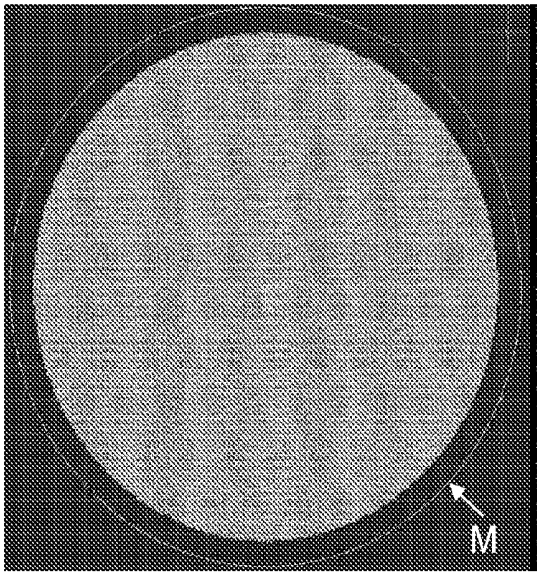


Fig. 4A

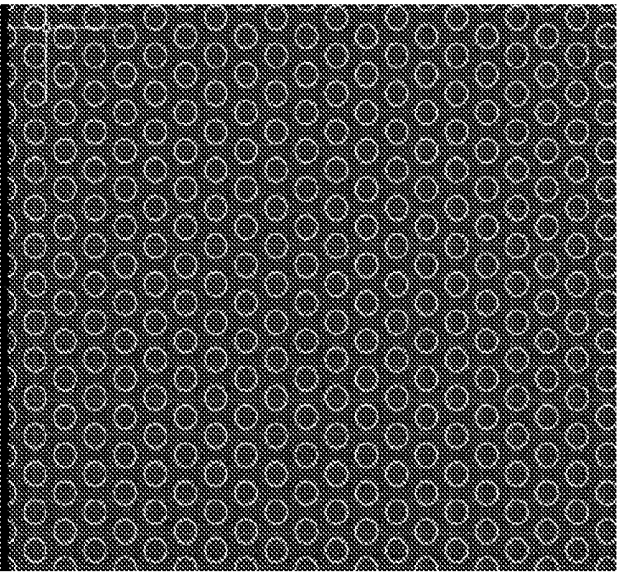


Fig. 4B

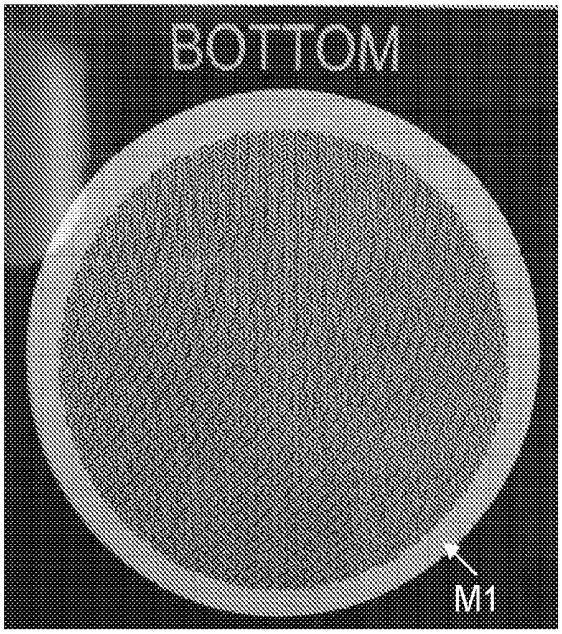


Fig. 5A

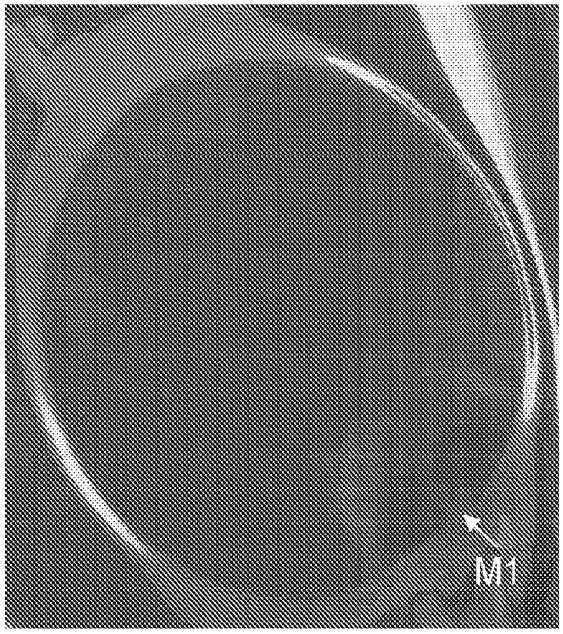


Fig. 5B

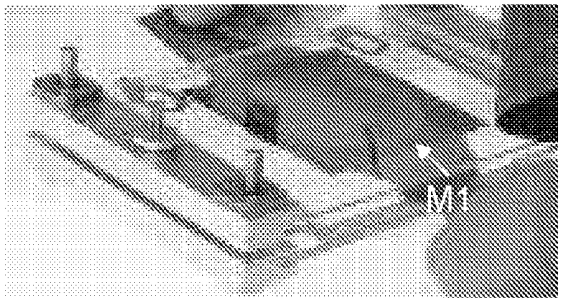


Fig. 5C

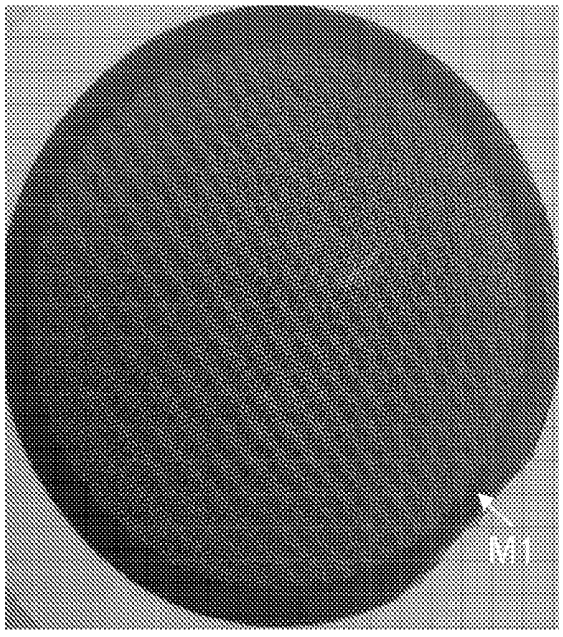


Fig. 5D

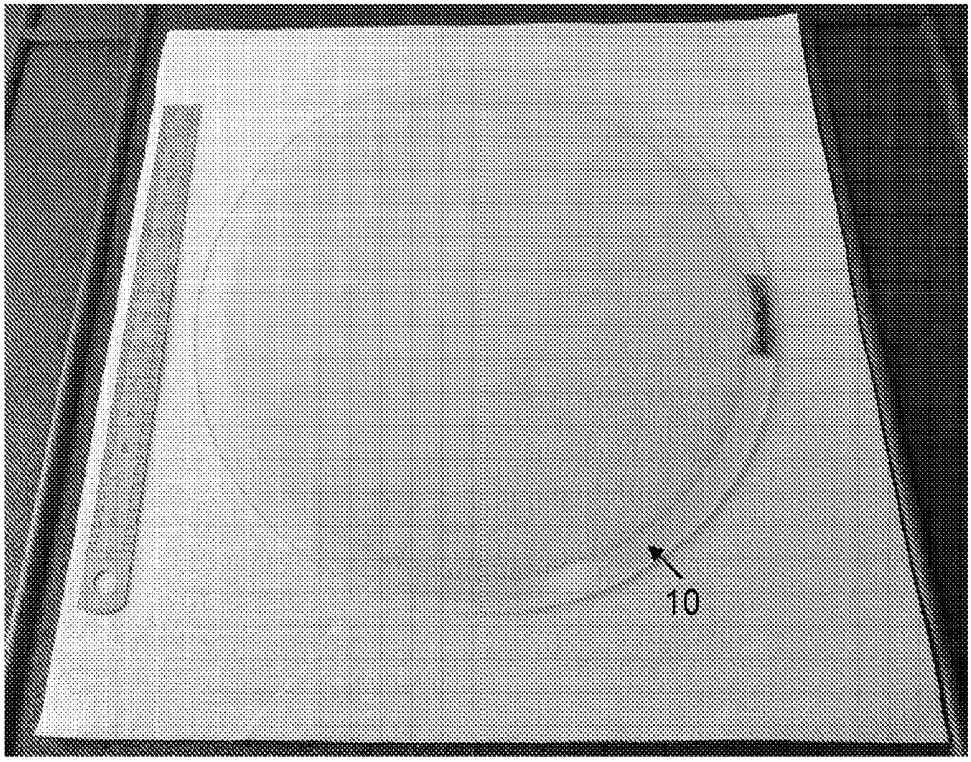
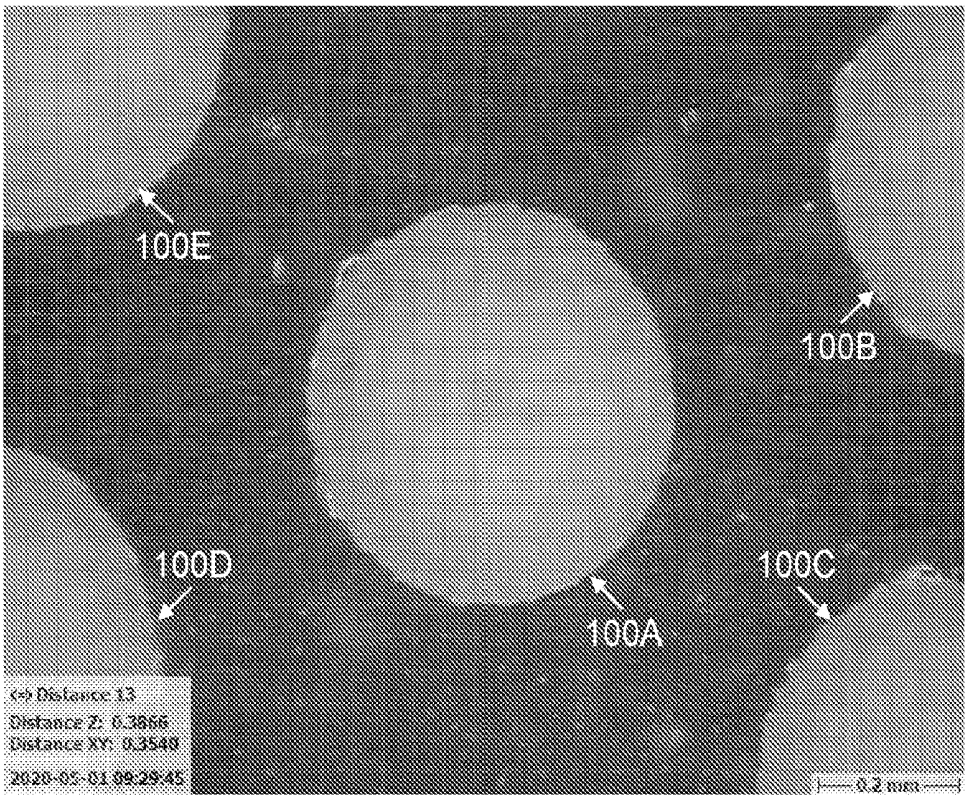

10

Fig. 6A


100E
100B
100D
100A
100C
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Distance XY: 0.3540
0.2 mm

Fig. 6B

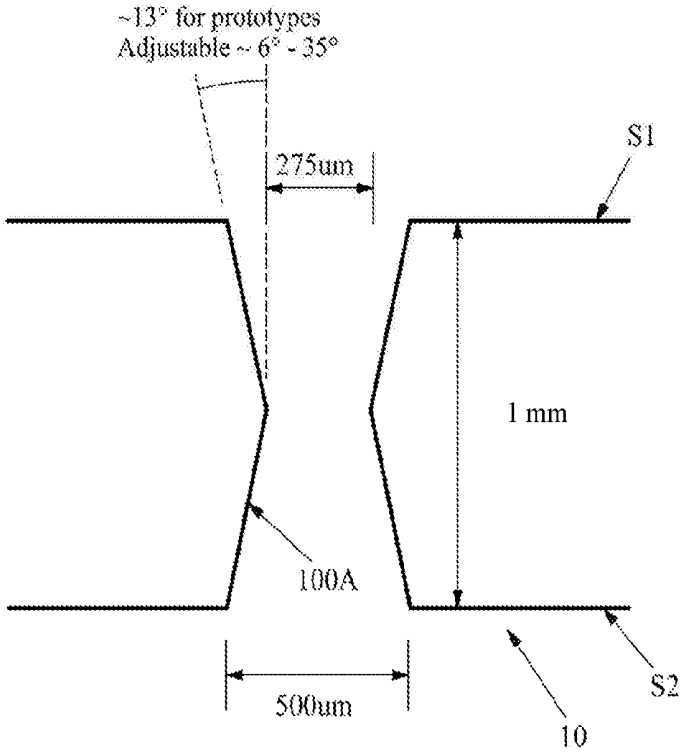
~13° for prototypes
Adjustable ~ 6° - 35°
275um
S1
1 mm
100A
500um
10
S2

Fig. 6C

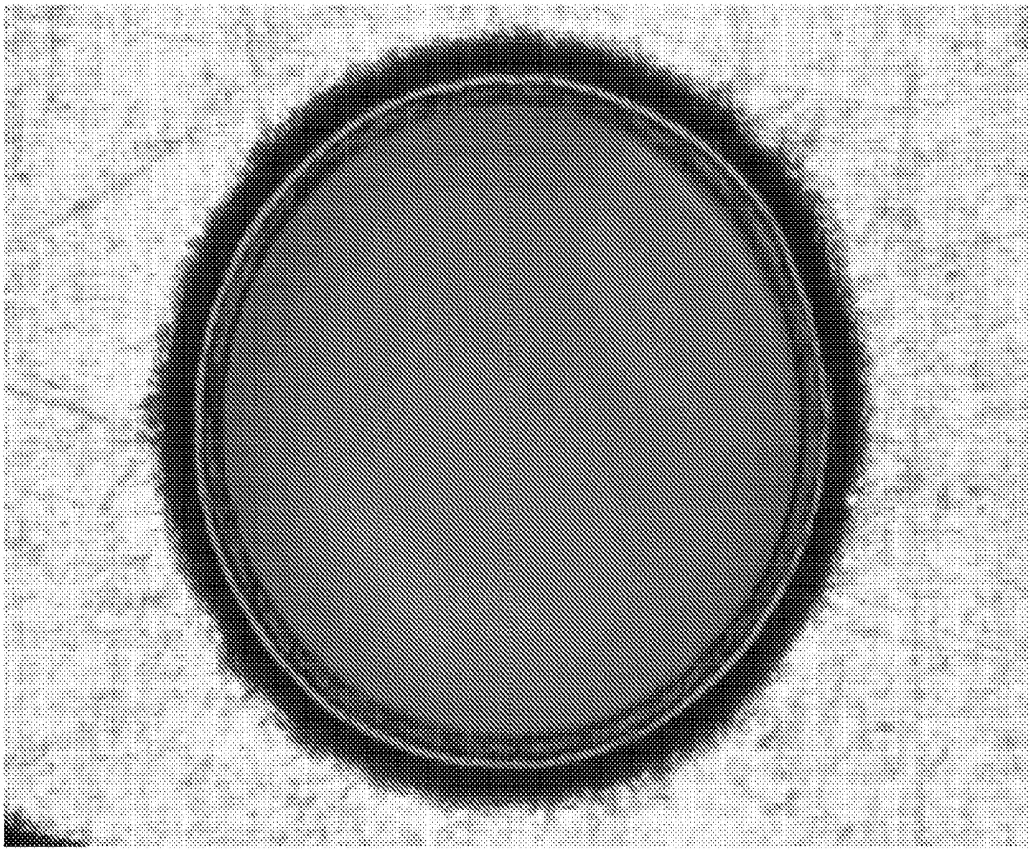

Fig. 6D

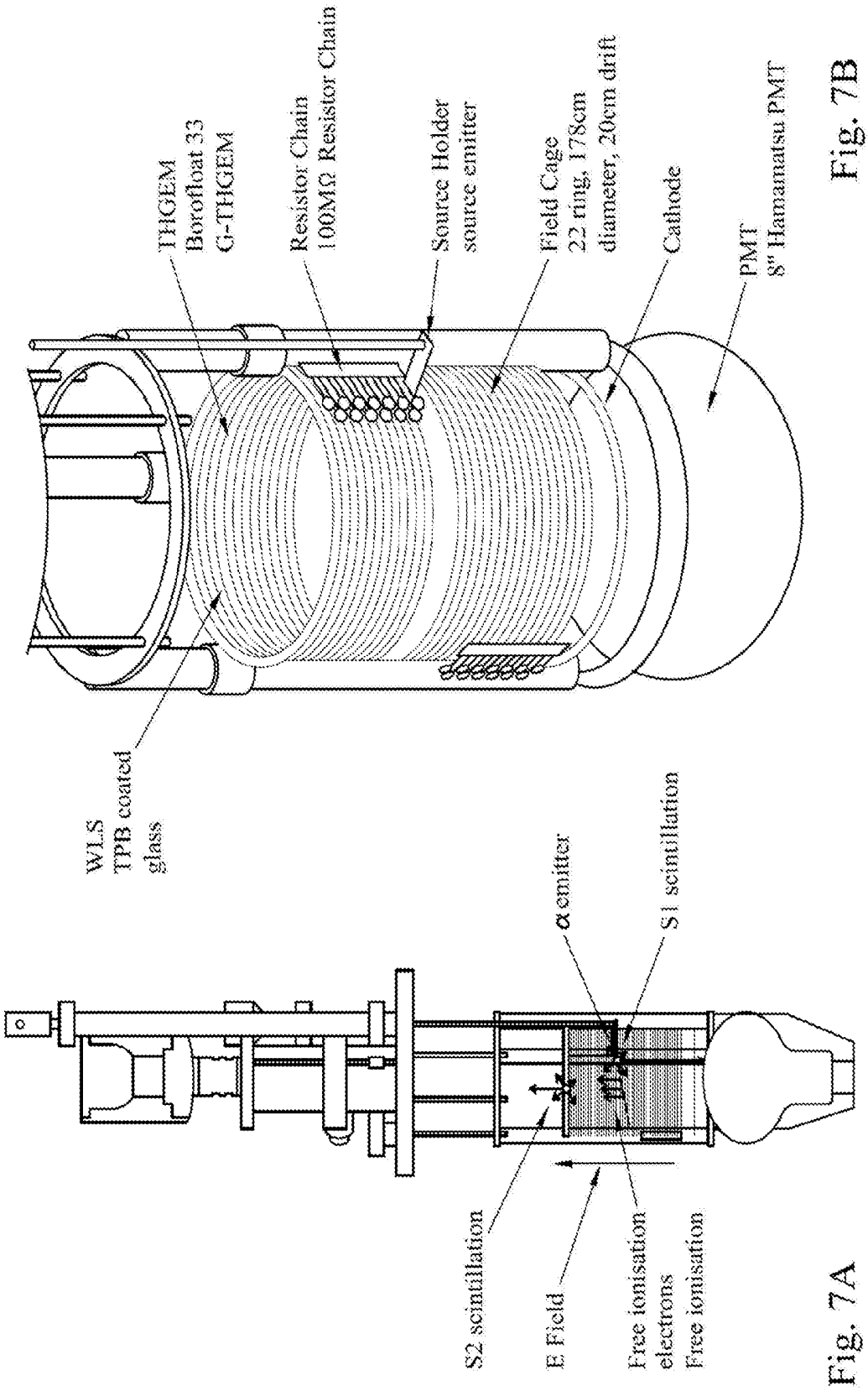
S2 scintillation
E Field
Free ionisation electrons
Free ionisation
α emitter
S1 scintillation
WLS TPB coated glass
THGEM Borofloat 33 G-THGEM
Resistor Chain 100MΩ Resistor Chain
Source Holder source emitter
Field Cage 22 ring, 178cm diameter, 20cm drift
Cathode
PMT 8" Hamamatsu PMT

Fig. 7A

Fig. 7B

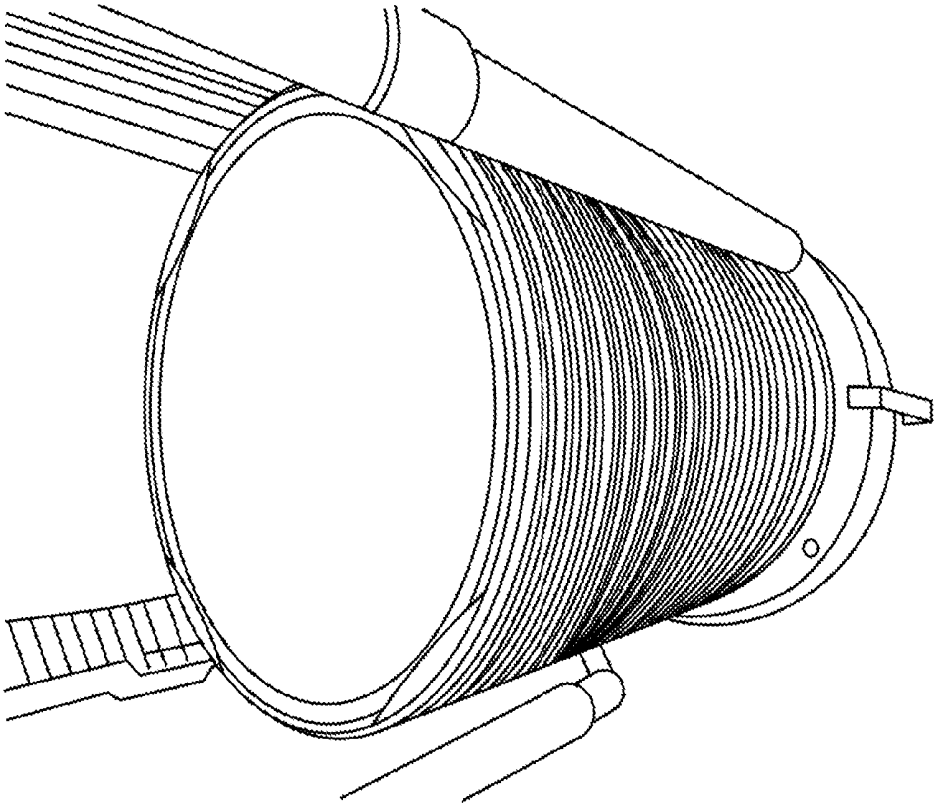

Fig. 7D

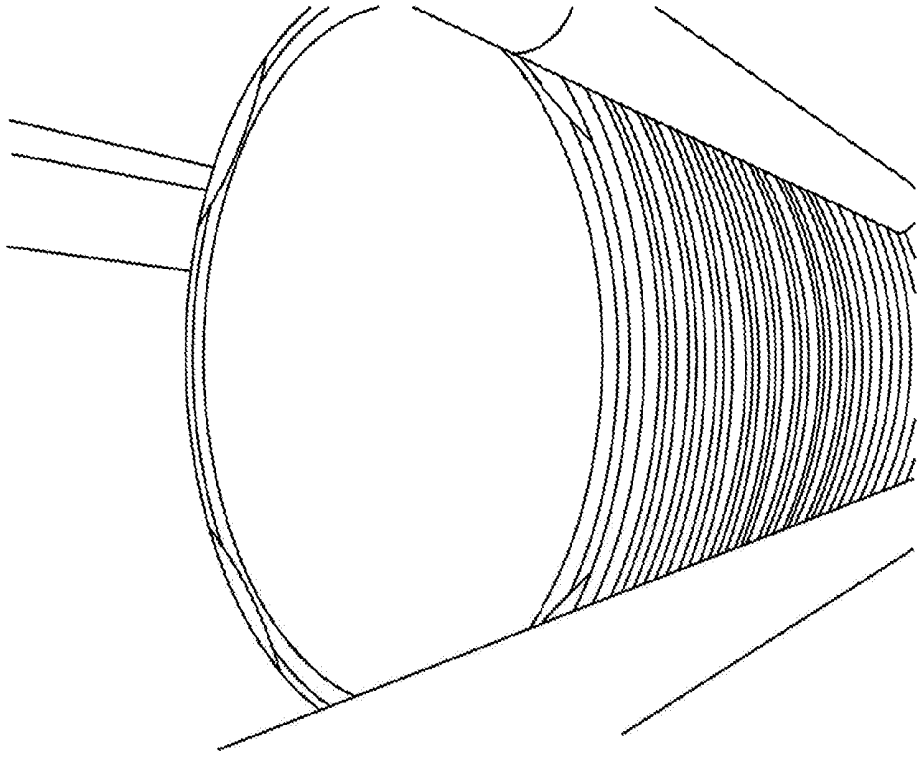

Fig. 7C

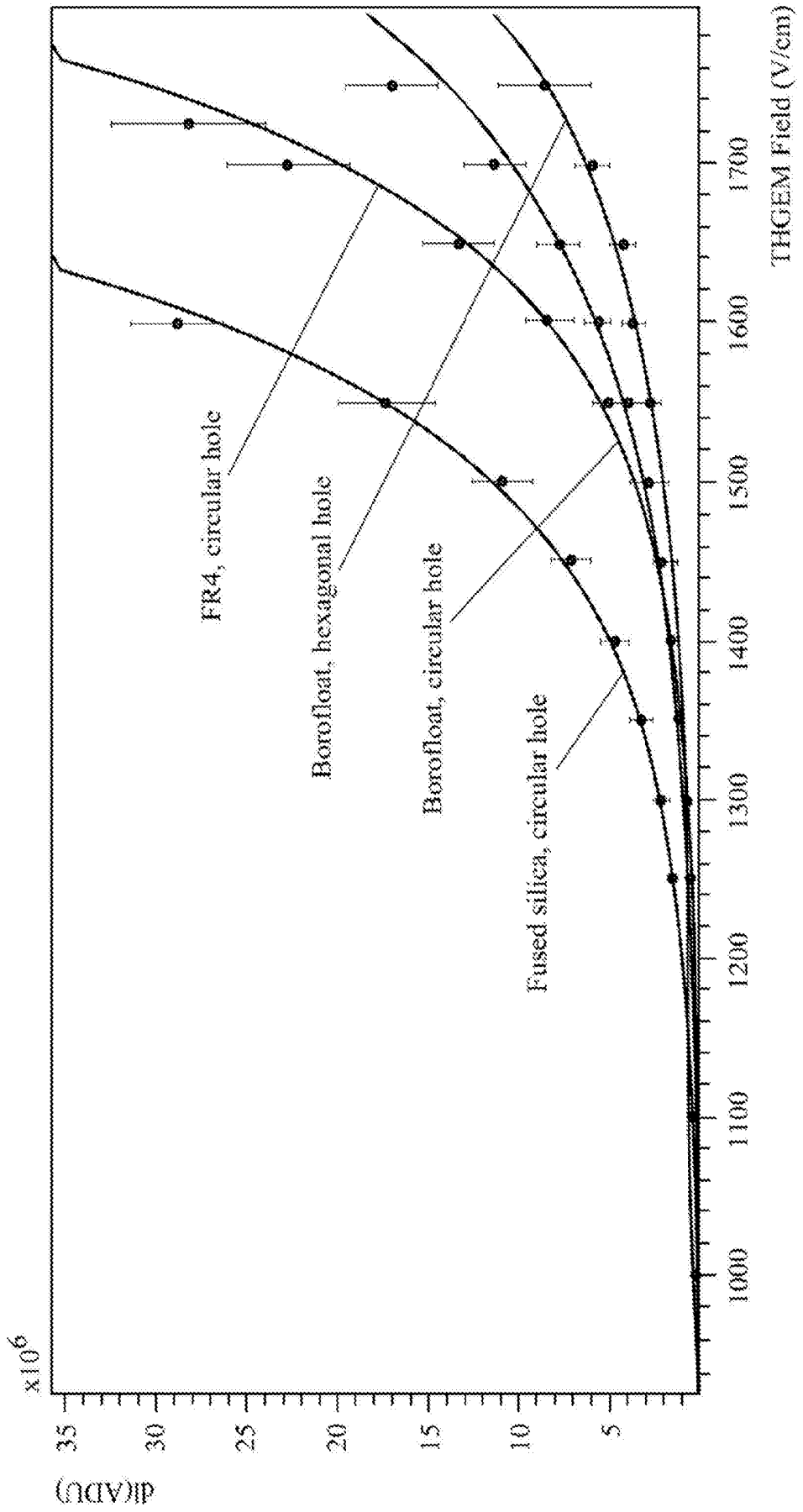
dI(ADU)
x10^6
35
30
25
20
15
10
5
1000
1100
1200
1300
1400
1500
1600
1700
THGEM Field (V/cm)
FR4, circular hole
Borofloat, hexagonal hole
Borofloat, circular hole
Fused silica, circular hole

Fig. 8

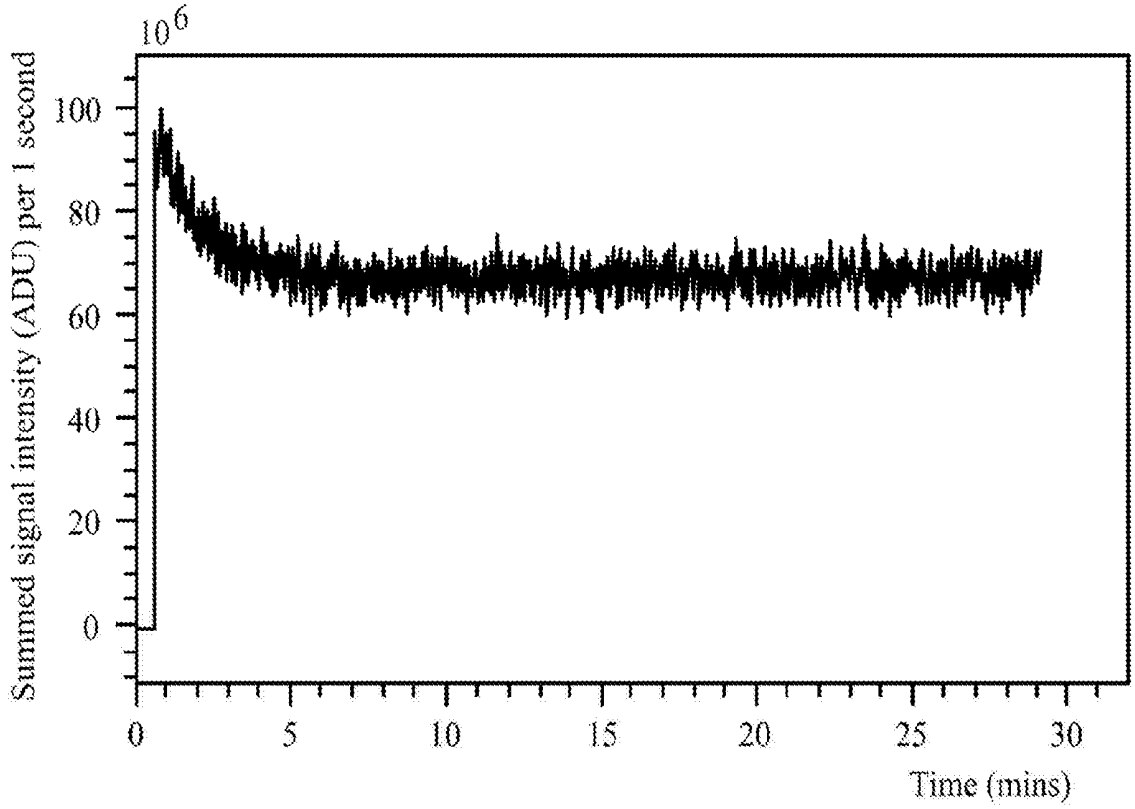
10^6
Summed signal intensity (ADU) per 1 second
100
80
60
40
20
0
0
5
10
15
20
25
30
Time (mins)

Fig. 9A

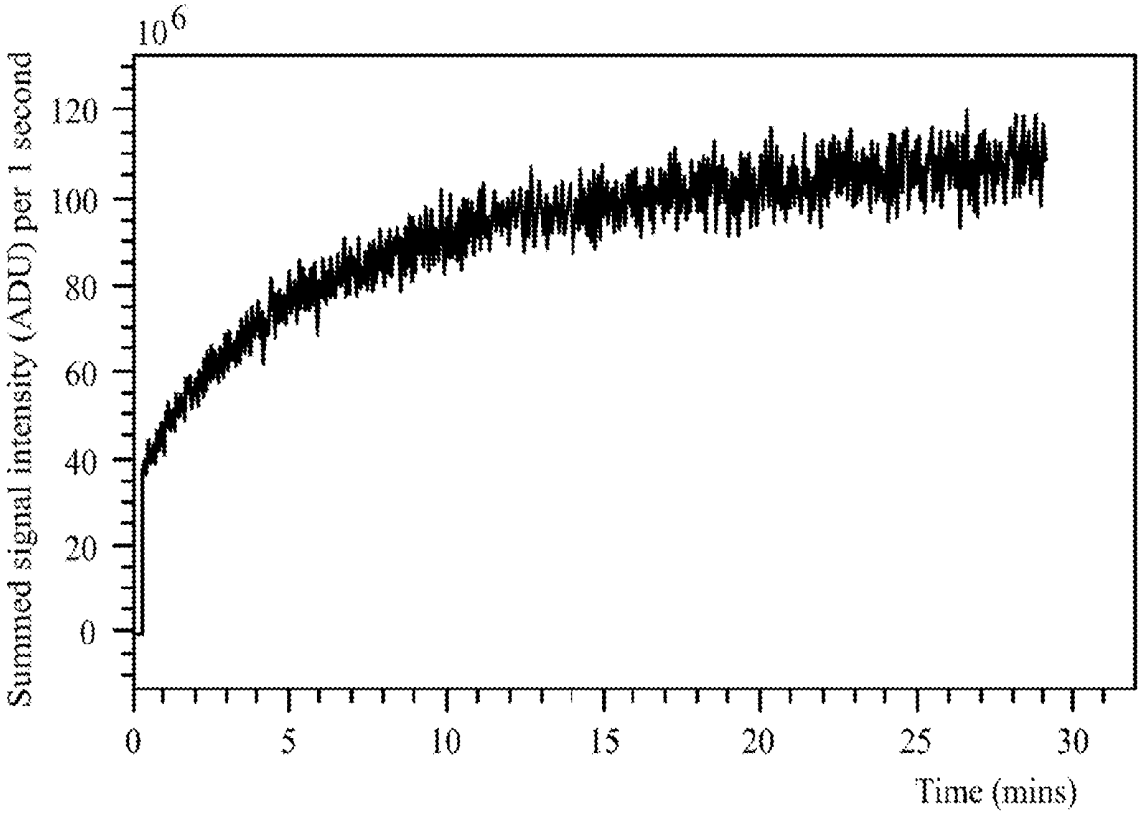
10^6
Summed signal intensity (ADU) per 1 second
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Time (mins)

Fig. 9B

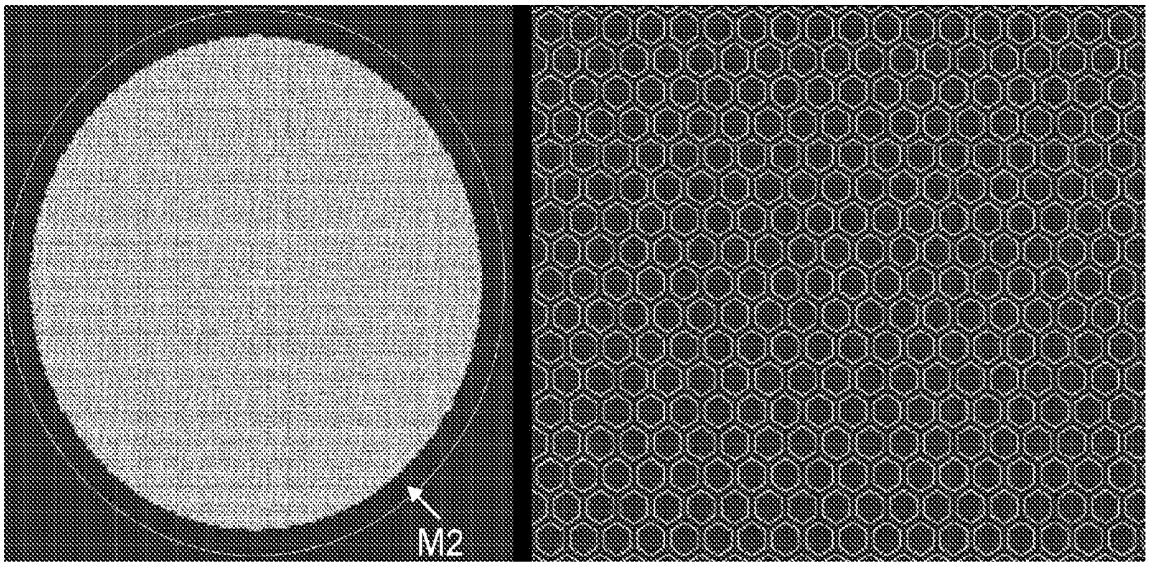

Fig. 10A Fig. 10B

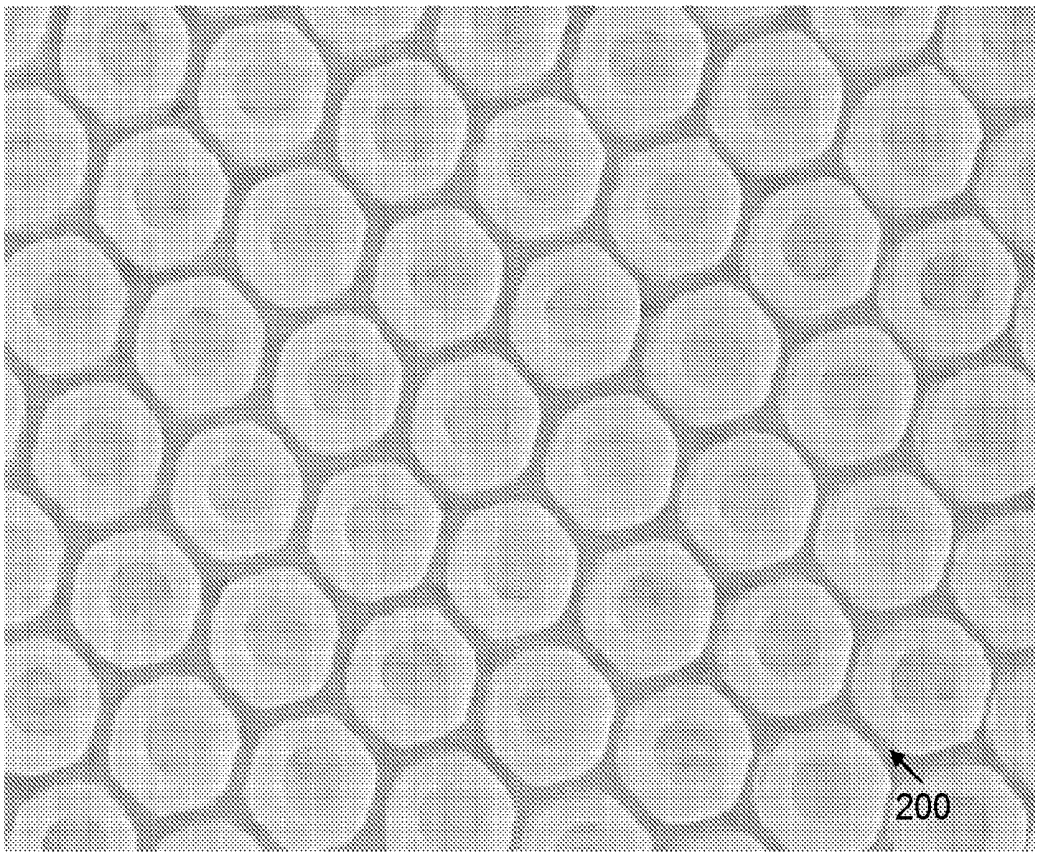

Fig. 11

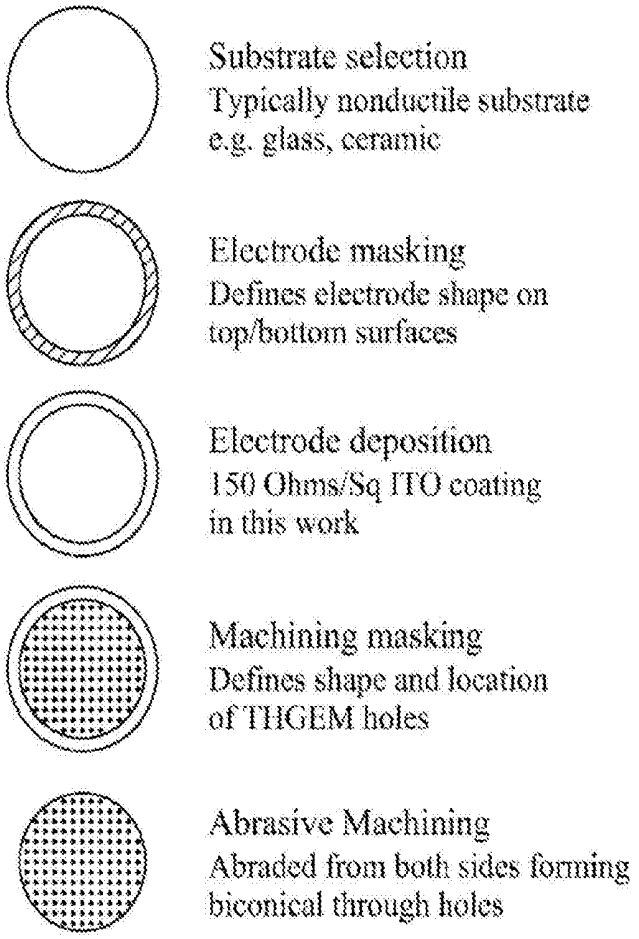
Substrate selection
Typically nonductile substrate
e.g. glass, ceramic
Electrode masking
Defines electrode shape on
top/bottom surfaces
Electrode deposition
150 Ohms/Sq ITO coating
in this work
Machining masking
Defines shape and location
of THGEM holes
Abrasive Machining
Abraded from both sides forming
biconical through holes

Fig. 12

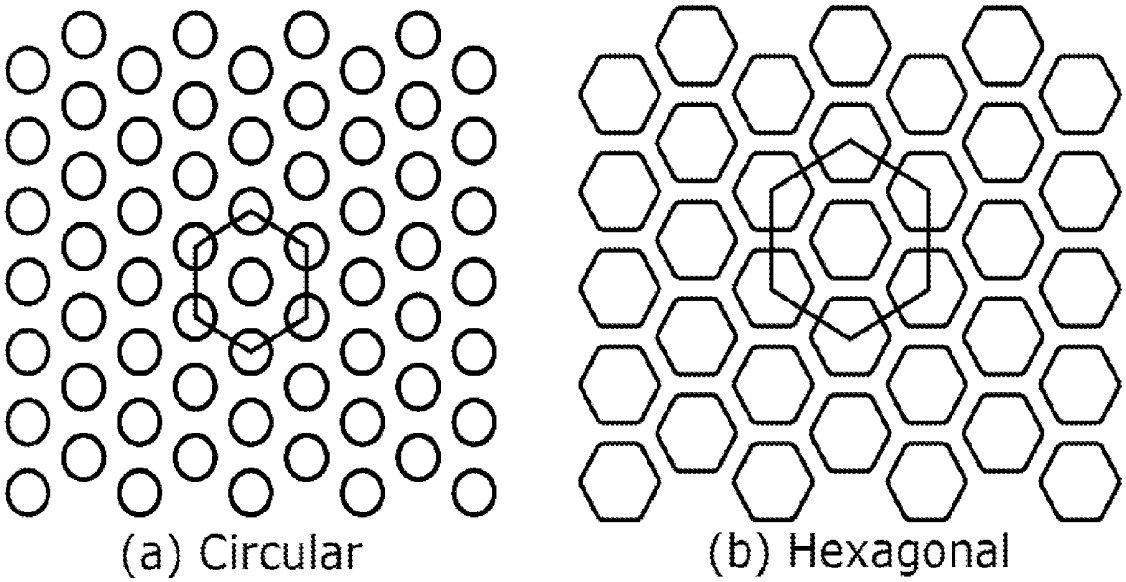
(a) Circular
(b) Hexagonal

Fig. 13

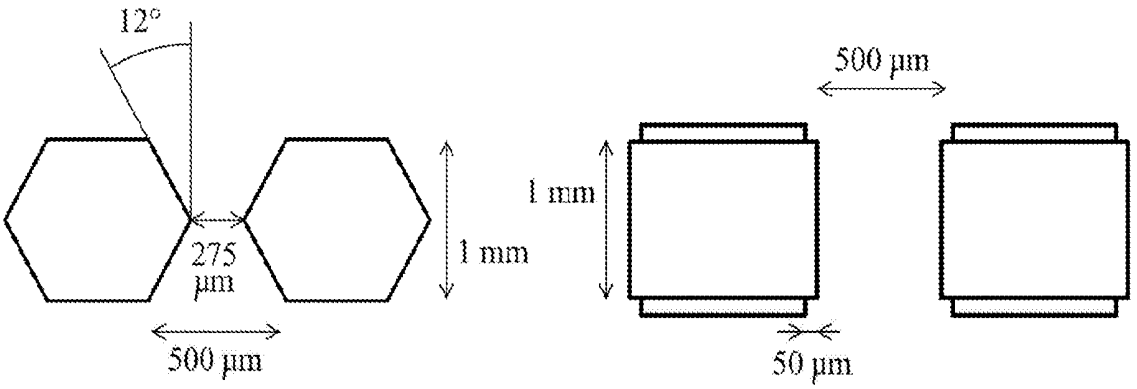
12°
275 µm
1 mm
500 µm
(a) G-THGEM
500 µm
1 mm
50 µm
(b) THGEM

Fig. 14

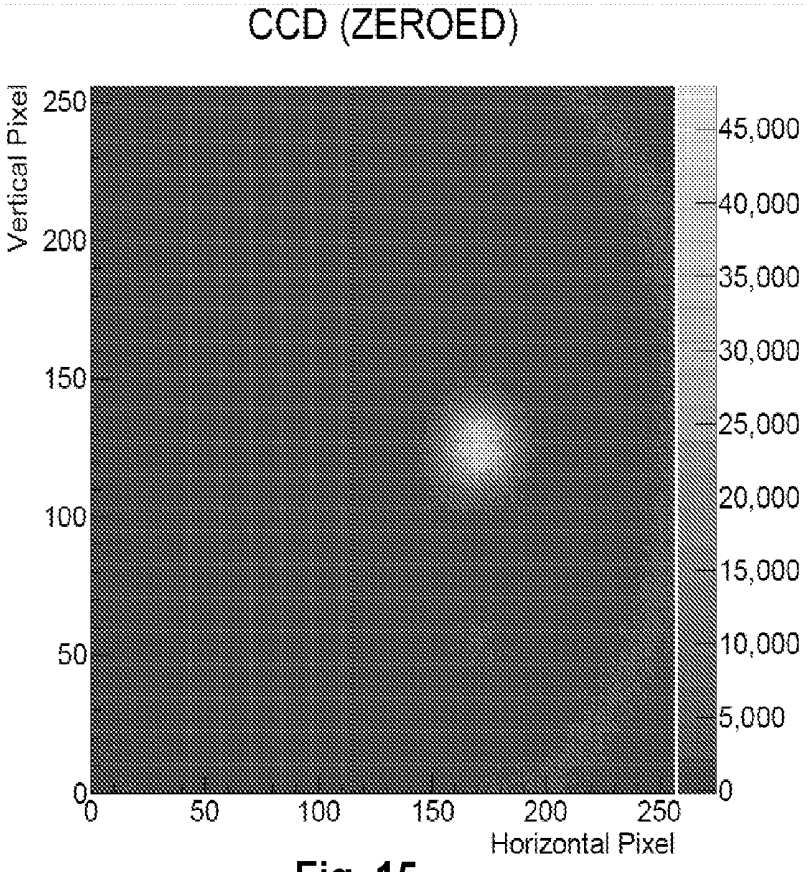
CCD (ZEROED)
Vertical Pixel
250
200
150
100
50
0
0
50
100
150
200
250
Horizontal Pixel
45,000
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0

Fig. 15

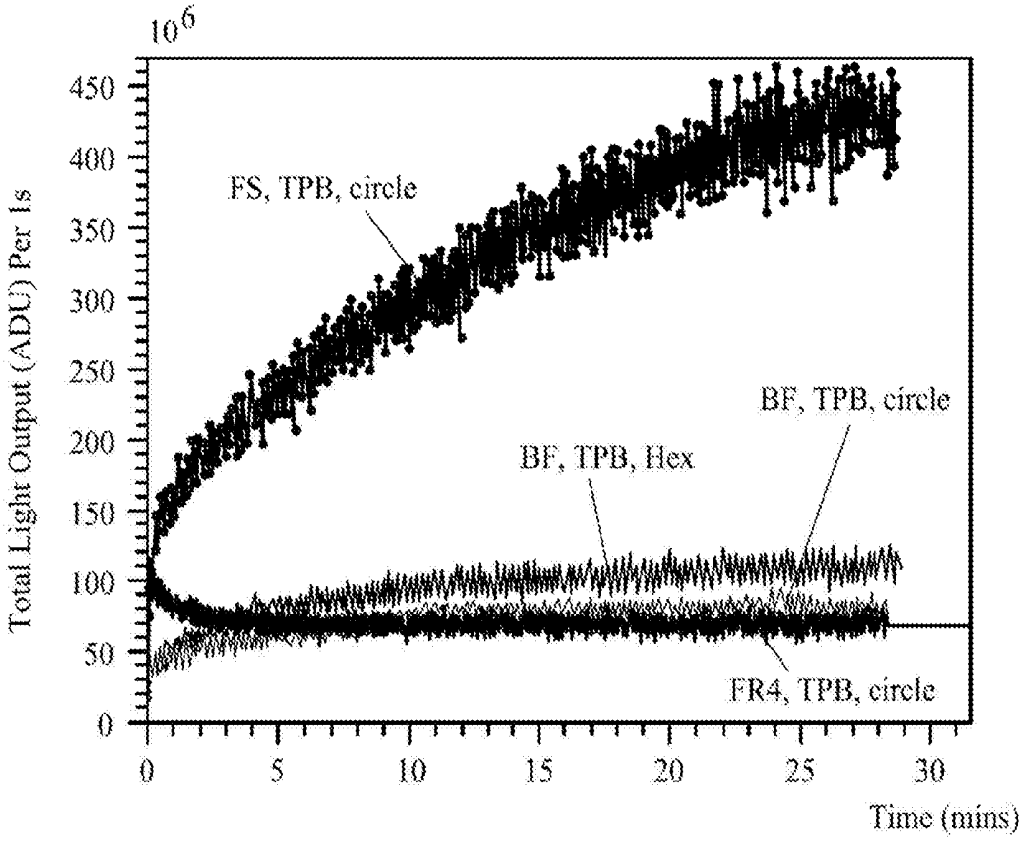

Fig. 16A

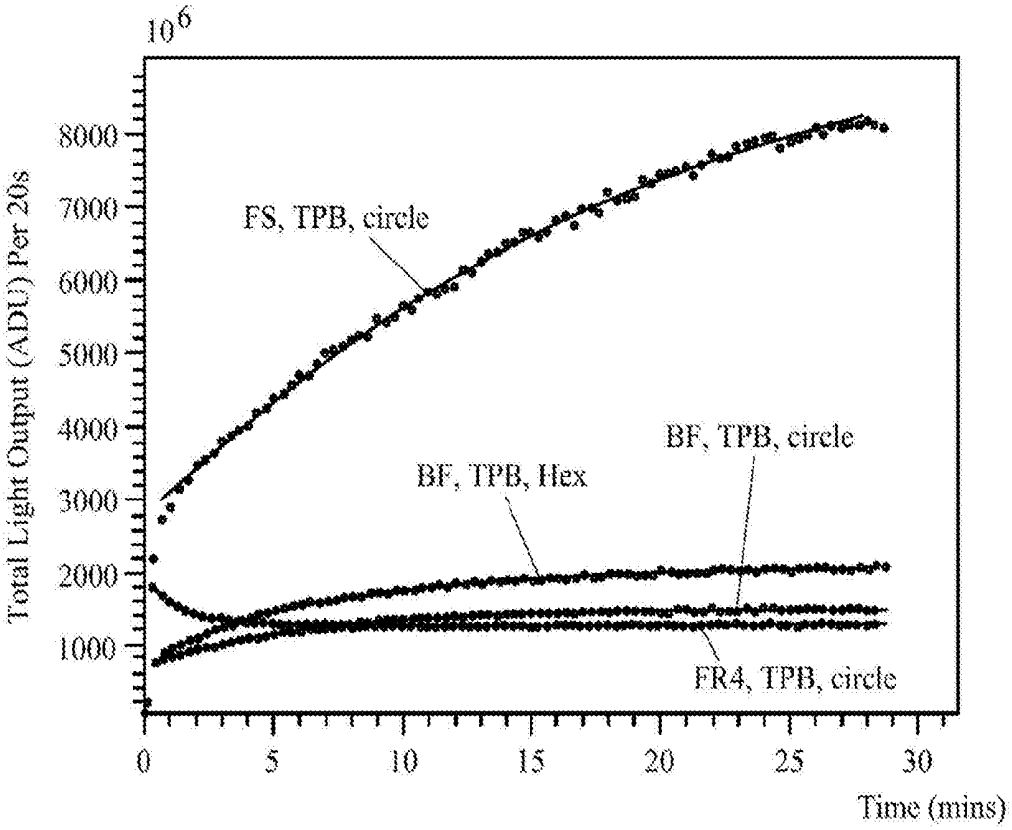

Fig. 16B

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2021/053233

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01J43/24
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 109 148 253 B (UNIV SCIENCE & TECHNOLOGY CHINA) 3 January 2020 (2020-01-03)	1-11,21
A	claim 1; figures 1-6	13,14
X	US 2013/267056 A1 (FUSHIE TAKASHI [JP] ET AL) 10 October 2013 (2013-10-10) paragraphs [0002], [0077], [0096], [0097]; figures 1,13	12-21

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 February 2022	01/03/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Peters, Volker

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TAKAHASHI HIROYUKI ET AL: "Development of a glass GEM", NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH. SECTION A, vol. 724, 31 December 2013 (2013-12-31), pages 1-4, XP028672795, ISSN: 0168-9002, DOI: 10.1016/J.NIMA.2013.04.089 page 2; figure 1; table 2 -----	12-21
X	BRUNBAUER FLORIAN M ET AL: "Combined Optical and Electronic Readout for Event Reconstruction in a GEM-Based TPC", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, IEEE, USA, vol. 65, no. 3, 1 March 2018 (2018-03-01), pages 913-918, XP011678964, ISSN: 0018-9499, DOI: 10.1109/TNS.2018.2800775 [retrieved on 2018-03-14] page 914 - page 915; figure 1 -----	12-21

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2021/053233

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 109148253 B	03-01-2020	NONE	
US 2013267056 A1	10-10-2013	DE 112011103995 T5	22-08-2013
		JP 5948249 B2	06-07-2016
		JP WO2012073758 A1	19-05-2014
		TW 201234411 A	16-08-2012
		US 2013267056 A1	10-10-2013
		WO 2012073758 A1	07-06-2012