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InGrid: Pixelated Micromegas detectors for a Pixel-TPC

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Within the LCTPC collaboration several possibilities to build a time projection chamber for a linear collider are studied. In all concepts, micro-pattern gaseous detectors (MPGD) are used as amplification structure. Compared to the traditional pad-based readouts used in most cases, a pixelated TPC is a new approach.
Only pixel ASICs can reflect the high granularity of MPGDs from the readout side. The idea to combine these two technologies was already conceived ten years ago. Such devices, called InGrids, are produced in a photolithographic process, when a grid is post-processed on a Timepix ASIC.
While the first InGrids were built on a single chip basis at the University of Twente, today whole wafers with 107 chips can be processed at the Fraunhofer IZM Berlin. Such a full wafer production is one cornerstone on the way to a pixel-TPC. As a first step, a demonstrator module with about 100 InGirds is under development in our group. Another key element for this project is the system to read out such a module. The Scalable Readout System (SRS), developed by the RD51 collaboration, is suitable for this task as it is based on a modular structure, that can be extended from a single chip readout to larger systems.
In a test beam campaign with a sub-component of the demonstrator module the readout system, the InGrid detectors and other components were successfully tested. Besides these results, the roadmap to a pixel-TPC demonstrator will be presented.

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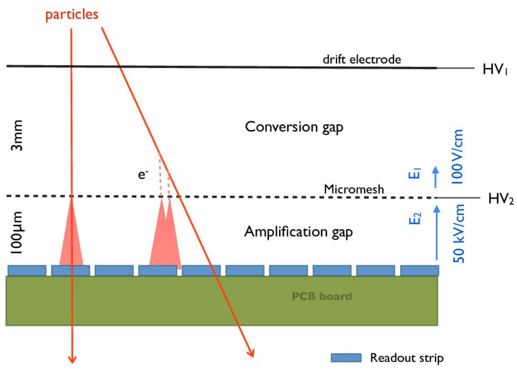

Figure 1: Schematic drawing of a Micromegas.

1. Introduction

Micro-pattern gaseous detectors like Micro-Strip Gas Chambers (MSGC), Gas Electron Multipliers (GEM) and Micro-Mesh Gaseous Structures (Micromegas) were an outcome of the advancing development in photo-lithography in the late 1980s [1]. The cell size was reduced from $O(1)$ mm for the previous wire technology to $O(10)$ µm for MPGDs. These devices are mainly used in the field of particle and nuclear physics in order to detect ionising particles. The Integrated Grid (InGrid), dealt with in this paper, is a special type of Micromegas.

1.1 Micromegas detector concept

The Micromegas, as one of the MPGDs, was invented by Ioannis Giomataris in 1996 [2]. It consists of a gas volume between two parallel plates, separated in two parts by a fine grained mesh or grid, see Figure 1. The pitch is in the order of several tens of micro-meters. The upper volume is called the drift region. Its dimensions depend on the type of detector to be used. It ranges from millimeters for a vertex [3] or X-ray detector [4] to several meters for a Time-Projection Chamber (TPC) [5]. In this region an ionising particle interacts with the detector gas molecules and electron-ion pairs are released (primary ionisation). Due to an electric field in the order of $100\,\mathrm{V/cm}$ applied between the cathode at the top of the detector and the mesh or grid, the electrons drift towards the latter. The ions are pulled towards the cathode and are neutralised there. Another electric field in the order of $50\,\mathrm{kV/cm}$ is applied in the same direction between the mesh or grid and the anode at the bottom of the detector. When an electron of the primary ionisation enters this volume called amplification region, it will be accelerated until it has enough energy to itself ionise gas molecules. The released electrons are accelerated again and an avalanche of electrons is created. After this process called gas amplification, in the order of 1000 secondary electrons arrive at the anode underneath the hole where the primary electron has entered. Charge sensitive electronics can be used in order to measure the signal generated by the electron avalanche. The gap between the anode and the mesh or grid is in the order of $100\,\mu\mathrm{m}$. The spread of the charge avalanche is about $20\,\mu\mathrm{m}$, depending on the gas. The anode plate is segmented to resolve the position of the avalanche and hence the primary electron. There are two ways to achieve a spatial resolution that is in the same order as the avalanche size. One option is to use pads or strips with a cell size of about 1 mm in combination with a resistive material covering the anode. The charge of the avalanche spreads on top of this resistive layer and the signal is detected by several pads or strips with different signal strength. By means of the center of gravity method, the position of the avalanche can be reconstructed. Another option is to use electronics that has the same cell size as the avalanche spread. This can only be achieved by using an ASIC as readout. An advantage of this option is, that the cell size of the MPGD is reflected from the readout side. Hence, every primary electron can be detected if the gas gain is high enough such that the amplified avalanche size exceeds the threshold of the discriminator in the pixel.

1.2 Pixelated MPGDs

The ASIC used in our experiments is the Timepix chip [6]. It has an array of 256×256 pixels with a pitch of $55\,\mu$m and an active area of $1.4\,\text{mm} \times 1.4\,\text{mm}$. Each pixel hosts a charge sensitive amplifier, a single threshold discriminator and a counter logic with 14 bit controlled by a clock. There are two main modes a pixel can be configured in: either to count the number of clock cycles the signal is over threshold (Time Over Threshold, TOT) or to count the number of clock cycles form the moment the signal exceeds the threshold until a chip-wide shutter closes (Time Of Arrival, TOA). Hence, besides the spatial information, the charge (from a TOT calibration) or the arrival time of an avalanche can be measured.

In 2004 a Micromegas was combined with a pixel ASIC for the first time [7]. A standard Micromegas mesh was spanned over the chip using a frame and spacers. However in this setup the pattern of the pixel is not aligned to the holes in the mesh.

Already in this first publication the long term goal to build a monolithic device, called Timepix-Grid, was mentioned. This device, now called InGrid, is a pixel ASIC with the grid post-processed on top of it. In 2006 the production process of the grid was tested on a bare silicon wafer [8] followed by an optimisation study for complete InGrids in 2009 [9]. The development was pioneered by the University of Twente/MESA+ and NIKHEF. In the process described in section 2 the alignment of pixels and holes can be achieved as well as a uniform gap and hole size. Such a type of detector has some advantages compared to MPGDs with pad readout.

The occupancy of a fine grained MPGD with pixel readout is significantly reduced with respect to a pad readout. This increases the rate capability of such devices.

Due to the high granularity, the pattern recognition of a pixelated MPGD is able to identify properties of the ionisation like polarisation, delta electrons and can distinguish between different particles. Also, a direct measurement of a converted photon can be measured by single electron counting. An InGrid detector has shown a resolutions σ_e/e of 5 % for the photo peak of Fe^{55} photons in an Argon Isobutane 95/5 gas mixture [11].

The production process of an InGrid assures a uniform gap distance leading to a uniform gas gain over the whole chip. The gain of the detector can be measured with a high precision. Hence, also the complete collected charge is a measure for the energy deposition of the particle. The InGrid detector has shown a resolution σ_e/e of 6.6 % for the photo peak of FE^{55} photons in an Argon Isobutane 95/5 gas mixture [11].

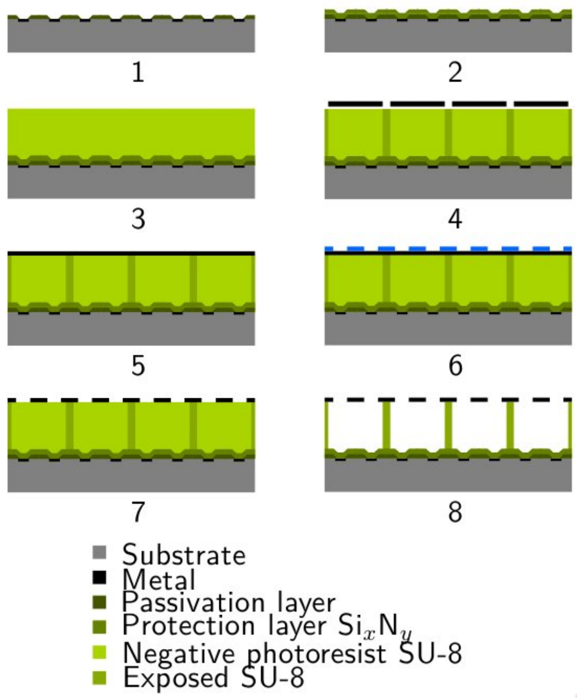

Figure 2: The eight main steps for the wafer scale the InGrid production.

Using the energy deposition information mentioned above, a dE/dx measurement of passing particles is possible by just pixel counting or complete charge measurement.

2. InGrid production

Since 2009 InGrids were produced on a single chip basis at MESA+ at the University of Twente [12]. In 2011 the production process was transferred to the Fraunhofer IZM in Berlin, where a whole 8 inch wafers with 107 Timepix chips can be processed in one run. The full wafer production was necessary due to the high demand in the gaseous detector community. In several test batches, the fabrication process was optimised, until InGrids were produced that deliver similar results then those of the single chip production. More details and test results can be found in [13]. The eight main steps of the microelectronic planar technology used to produce InGrids out of a whole wafer are shown in Figure 2.

1 A bare Timepix wafer is cleaned to remove dust particles.

2 To protect the charge sensitive pads of the Timepix chip against sparks in the amplification gap, a resistive layer of Si_x N_y is deposited on the wafer. The height of this layer is typically 4 µm or 8 µm. Before this process step, the bonding pads of the chips are covered with a polyimide that can later be removed.

3 The amplification gap is formed by the negative photoresist SU-8 that is dissolved later in the process. It has a height of 50 µm.

4 The pillars inside the gap supporting the grid are built by exposing the SU-8 with a mask.

5 To build a grid of about 1 μm thickness several sputtering runs have to be applied in order to not heat up the underlying SU-8 too much.

6 After the aluminium layer is sputtered on the SU-8 with a sufficient thickness, a photoresist mask is put on that layer.

7 The mask protects the aluminium from the chemicals that are used in this step to form the holes of the grid.

8 Before dissolving the unexposed SU-8 and other residues, the wafer is diced into individual chips.

3. The pixel-TPC

The InGrid is used in the CAST experiments at CERN [4] and there is also the idea to use it in the DARWIN experiment [14]. In this publication we will focus on the application of an InGrid detector in a Time-projection chamber (TPC).

3.1 TPC prototype

For the International Large Detector (ILD), one of the two planned detectors at the International Linear Collider (ILC) currently in the discussion to be built, a TPC is foreseen as tracking detector. Its momentum resolution aims to be ten times better than currently the detectors at the Large Hadron Collider are. In order to study and compare technology to read out such a TPC, the Linear Collider TPC Collaboration has set up a prototype at DESY [15]. The endplate of this prototype is a cut-out of the real planed ILD TPC endplate and can host up to seven modules. It has a diameter of 72 cm. The maximum drift distance is 56.76 cm. The TPC field cage is embedded in a 1 T magnet called PCMAG.

3.2 Pixel-TPC demonstrator

To study the properties of such a detector and to boost the development of this technology, a test beam was undertaken at the TPC prototype in 2013 [16] [17] with a module of eight InGrid chips, see Figure 3. In a preliminary analysis, the track reconstruction in the framework of the MarlinTPC software package was successfully used. First results, as for example the number of hits per track length or the single point resolution, can be found in the publications.

In further analyses, the characteristics of tracks will be studied, as for example delta electrons as shown in Figure 4. Detecting and removing those before the track reconstruction could lead to a higher precision. Because of the high granularity, the InGrid detector should have a good double track resolution. Events like shown in Figure 5 will be studied and algorithms have to be found to resolve what can clearly be seen by eye.

The single point resolution has to be further investigated. It is still heavily affected by field distortions at the interception between drift and amplification region. Moreover, the resolution of

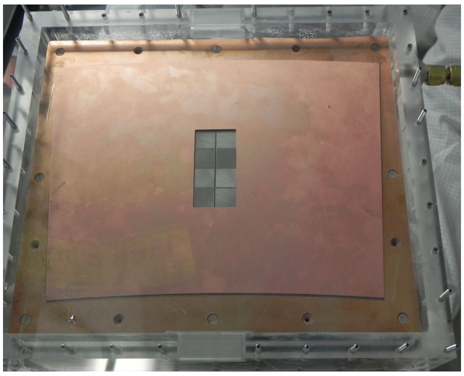

Figure 3: A Module including eight InGrid chips for the large Prototype of the LCTPC collaboration at DESY.

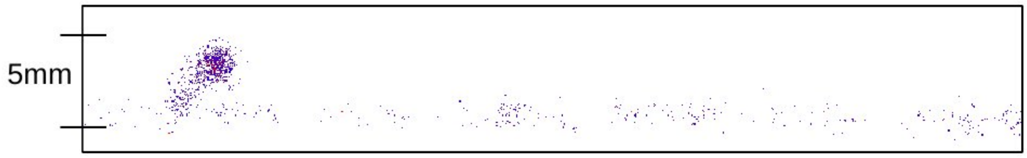

Figure 4: Online event display of a recorded track with InGrid detectors. A delta electron radiated off the track is visible on the left.

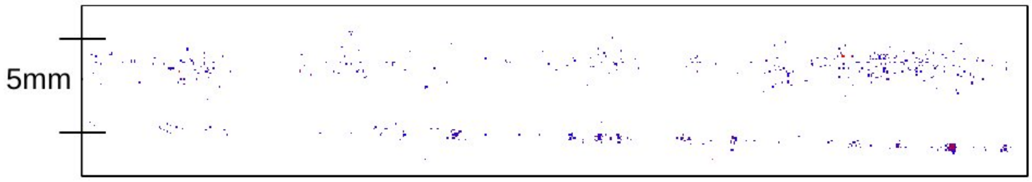

Figure 5: Online event display of a recorded double track event with on InGrid detectors.

the device for a whole track has to be studied.
Besides the challenges of the analysis, the feasibility of a pixel TPC has to be proven. For that reason a module for the TPC prototype largely covered with InGrid chips has to be built. Such a module is currently in design in our group in Bonn. It will host 96 InGrid chips grouped on 12 octoboards. The mechanics, including a water cooling structure, is designed using CAD software, see Figure 6. Another study ongoing investigates the field distortions at the edges of the chips. In this area, due to the gaps between chips, the drift field is not homogeneous, see Figure 7. The idea is to cover the gap with an aluminium strip, see Figure 8. Powering of the module will also need some attention, as only during the shutter opening time all chips draw a large amount of current. Moreover a readout system based on the Scalable Readout System (SRS [18]) is developed. Its functionality was demonstrated in the testbeam. The system will be scaled up for the readout of the 96 chip module. Results will be presented in following publications.

4. Conclusion and outlook

Within the last 10 years a pixelated Micromegas , called InGrid, was developed. It combines

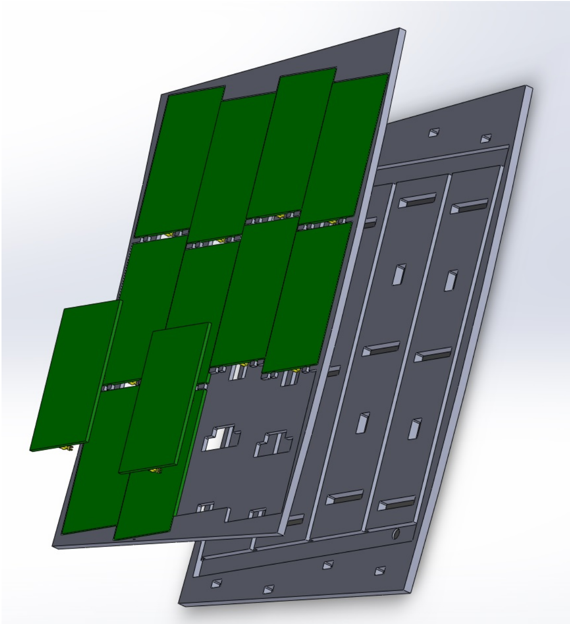

Figure 6: Explosion view of a CAD drawing of the mechanics and cooling structure for a 96 InGrid module.

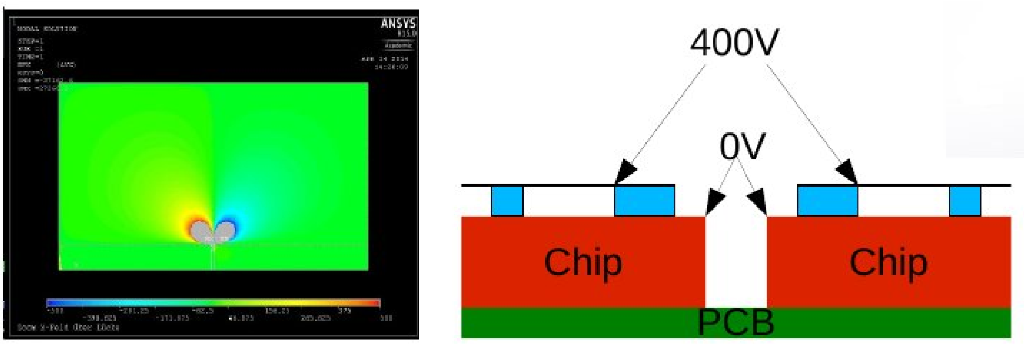

Figure 7: Simulation of the electric field in ANSYS, the configuration of the potentials can be seen on the right.

a Micromegas gas amplification stage with pixel readout. The grid is processed on top of the chip in a photolithographic process and is available in mass production on wafer scale. This detector is used in experiments and R&D in particle physics. A pixel TPC is one application of such a device. A module for a prototype TPC will be equipped with 96 InGrids. The module design and related studies are ongoing. With this module, the feasibility of a pixel TPC will be demonstrated.
An advanced version of the InGrid, called ceramic grid, will be developed soon. The advantage of such a device is, that besides the anode, also the grid will be covered with Si_x N_y. This will reduce the discharge probability and strength as well as the capacity and hence, the intrinsic noise of the detector.

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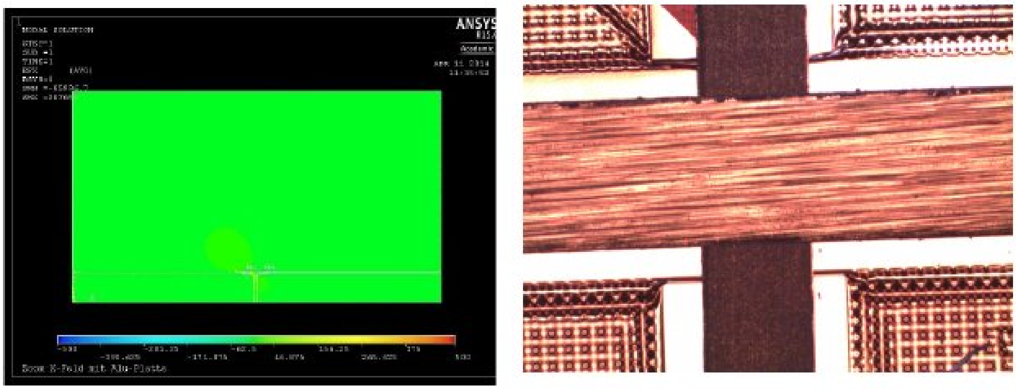

Figure 8: Simulation of the electric field in ANSYS with an aluminium strip covering the gap between chips. A microscope image of such a strip on top of a gap can be seen on the right.

Acknowledgments

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