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A test beam setup for the characterization of the Geiger-mode avalanche photodiode technology for particle tracking

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ABSTRACT

It is well known that avalanche photodiodes operated in the Geiger mode above the breakdown voltage offer a virtually infinite gain and time accuracy in the picosecond range that can be used for single photon detection. However, their performance in particle detection still remains unexplored. In this contribution, we are going to expose different steps that we have taken in order to prove the efficiency of the Geiger mode avalanche photodiodes in the aforementioned field. In particular, we will present a setup for the characterization of these sensors in a test beam. The expected results of the test beam at DESY and CERN have been simulated with Geant4 and will also be exposed.

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1. Introduction

The International Linear Collider (ILC) [1] and the Compact Linear Collider (CLIC) [2] are the two proposed e^+e^- high precision colliders which are currently in their technical design phase. The scope of these colliders is to provide measurements with unprecedented accuracy and precision in order to further study the results obtained at the Large Hadron Collider (LHC). Appropriate vertexing and tracking detector systems capable of precise vertex reconstruction and momentum measurement are a must in order to fully exploit the research potential of any particle accelerator. Nevertheless, ILC and CLIC put challenging requirements on detector systems since they will have to supply exceptional spatial resolution at high incoming rates [3]. At present time, there is no mature technology that can fulfill these specifications and new detector systems are being developed in parallel with the accelerator. Solid-state detectors concentrating most of the researches are based on CMOS monolithic pixel technologies. Leading sensor techniques are Charge Coupled Devices (CCDs) [4], Monolithic Active Pixel Sensors (MAPS) [5] and Depleted Field Effect Transistors (DEP-FETs) [6]. Alternative approaches are based on the Geiger mode avalanche photodiodes (GAPDs) [7,8] and Silicon-On-Insulator

(SOI) devices [9]. More recently, CMOS sensors exploiting the vertical integration technology (3D) have also gained interest [10]. Nevertheless, whereas SOI devices and 3D technologies are still at a very early stage of development, the basic studies have already been conducted with GAPD arrays.

A very important breakthrough in the development of a new sensor technology aimed to particle tracking is accomplished by subjecting the sensor to a series of test beam experiments. In a test beam, the response of a prototype detector to high energy particles is characterized. Amongst other parameters, detection efficiency, intrinsic resolution and Signal-to-Noise Ratio (SNR) are quantified. The results of the test beam may refute or validate the proposed sensor technology as a candidate for a vertexing or tracking detector system.

The first demonstration that CCDs can be used as tracking detectors was already done in 1983 in a CERN test beam, where these sensors showed a 98% detection efficiency and a spatial resolution in the range of 4.3–6.1 μm [11]. Since then, these devices have been used in several experiments, such as the VXD3 at the Stanford Linear Accelerator Center (SLAC) [12]. Some years later, specifically in 1999, the ability of MAPS to provide charged particle detection was proved for the first time on a Minimum Ionizing MOS Active (MIMOSA) I chip prototype at the Super Proton Synchrotron (SPS) at CERN [13]. Several generations of MAPS detectors have been tested at the CERN SPS so far [5]. The measurements have demonstrated a detection efficiency of 99.5%, a fake hit rate of 10^{-4} per pixel and a spatial resolution around

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2 μm [14]. In particular, the MIMOSA 26 sensor equips the EUDET/AIDA beam telescope [15], which at present time is an essential part of the test beam setup for new tracking detector candidates at several installations. The studies of DEPFETs' capabilities for tracking minimum ionizing particles started in 2005 at DESY [16] and have continued during the following years at the CERN SPS [17–19]. To be precise, DEPFET prototypes have exhibited a detection efficiency of 99.96%, a SNR larger than 110 and intrinsic resolutions around 1 μm . The DEPFET sensor will be used as a vertex detector in the Super KEK-B experiment (Belle II). For SOI technologies, the test beams have commenced recently at the Advanced Light Source (ALS) of the Lawrence Berkeley National Laboratory (LBNL) [20]. As a result of these experiments, a SNR of 15 has been reported.

In the case of GAPDs, although their extraordinary capabilities in photon detection are widely known [21], their performance in particle detection has not been investigated yet. In this work, a setup for the test beam of these sensors is presented. Special attention is paid to the GAPD detector that has been particularly designed for this purpose as well as to the satellite electronics. At current time, one or two GAPD test beams are already planned, depending on the availability. DESY, with a 6 GeV electron particle beam, is a first possibility. The second option is CERN, where the particle beam consists of 120 GeV pions. In order to know in advance the extent of multiscattering in the particle path introduced by the test beam setup, which can hinder or impede the reconstruction of the traces, simulations have been carried out by the Geant4 simulation toolkit. The results of these simulations will also be explained in this paper.

2. Device Under Test (DUT)

The GAPD detector (DUT) was prototyped with the standard High-Voltage AustriaMicrosystems (HV-AMS) 0.35 μm CMOS technology (h35b4). The detector was designed to have a sensitive area of $1 \times 1 \text{ mm}^2$ in order to facilitate the observation of particle traces. In addition, the sensor size was fixed to $20 \times 100 \mu\text{m}^2$ [22] to achieve a good fill factor (88%). The detector is organized in 10 rows (m) per 43 columns (n) of pixels. Each pixel of the detector combines a sensor and proper readout electronics (see Fig. 1 for pixel schematics). Both the sensor and the readout electronics have been monolithically integrated on a single CMOS die. Since the GAPD detector was designed to prove the efficiency of this technology in a test beam, neither the maximization of the fill factor nor radiation tolerance have been considered.

Fig. 1. Schematics of the proposed digital pixel.

The photodiode is implemented by means of a p^+ /deep n -tub junction, which is surrounded by a p -tub implantation set to prevent premature edge breakdown. Additionally, the corners of the sensor are rounded to avoid electric field peaks at the junction corners. The different pixels within a row share the same deep n -tub (common cathode), which increases the fill factor. Reverse bias overvoltages (V_{OV}) over the breakdown voltage (V_{BD}) are applied to the sensor cathode to operate the Geiger mode. The readout is performed at the anode or sensing node (V_S).

The detector can be operated in the gated mode of acquisition to reduce the probability to detect the sensor intrinsic noise. In this work, the gated operation is controlled by means of two external signals (RST and INH) implemented through MOS transistors (M_{N0} and M_{P0}) [23]. The sensing node V_S is connected to the readout electronics, which is based on a CMOS inverter (M_{P1} and M_{N1}) that converts the analog voltage generated as a result of a real or noise hit into a digital pulse. The CMOS inverter was designed to have a threshold voltage of $V_{DD}/2$ and a reduced propagation delay of 50 ps. The output of the inverter (V_{INV}) is fed into a dynamic latch (M_{N2} , M_{P2} and M_{N3}), which has been included to make in-pixel storage possible. The dynamic latch samples the node V_S when the sensor is 'on', whereas the value of the node V_S is stored in the node V_{LATCH} ('0' for no hit, '1' for hit) during the gated 'off' period. This performance is controlled by means of an external signal CLK1, which has been implemented through the MOS transistor M_{N2} . The duration of the sampling mode is called period of observation (t_{obs}).

To reduce the Dark Count Rate (DCR) and increase the SNR, a low V_{OV} is desired. However, low overvoltages are not allowed in this technology given that the threshold voltage of the n MOS transistors is set at 0.5 V. In order to overcome this drawback, the sensor and the readout circuit have different ground nodes, which are respectively GNDA and V_{SS} . By raising GNDA with regard to V_{SS} , low avalanche voltages can be easily detected by the CMOS inverter.

In order to control the outward data flow, a simple address circuit based on a pass gate (M_{N4}) has been placed between the dynamic latch and the output column line. The pass gate M_{N4} is controlled by means of an external signal $CLK2_m$, with $m=0-9$ (one control signal per row of the detector). The 10 rows are read sequentially during the gated 'off' periods of the detector. When the $CLK2_m$ signal is set high, the transistor M_{N4} is switched on and the dynamic latch feeds the output column line, which is directly connected to the output pad. Whereas the signal $CLK2_m$ is common to all the pixels of the same row, the output column line n is common to all the pixels of the same column. Consequently, when enabled by the $CLK2_m$ signal, the 43 columns of row m are simultaneously read out. Although this readout configuration needs 43 output pads ($V_{OUT,n}$, with $n=0-42$) plus 13 pads for the control signals (RST, INH, CLK1 and $CLK2_m$, with $m=0-9$), neither multiplexers nor selection decoders are needed. The whole detector, i.e. the information stored by the 10×43 pixels, can be read in approximately 100 ns.

3. Test beam setup

A schematic diagram of the setup for the GAPD test beam is depicted in Fig. 2. The setup is comprised of two DUTs, a reference system consisting of one Schottky detector and an EUDET/AIDA beam telescope, and a Trigger Logic Unit (TLU) which is used to distribute the trigger signal. The scope of the experiment is to test whether the GAPD technology detects high energetic particles and, if so, determine the efficiency of the technology and study different areas of sensitivity of the sensor. In addition, the efficiency of the GAPD technology in particle tracking will also

Fig. 2. Schematic diagram with DUTs and the satellite electronics for the test beam. The different elements are not to scale.

be tested. At least two layers of GAPD detectors are needed for this last purpose. Therefore, the setup for the test beam includes two DUTs. Each one of the DUTs is arranged in a Printed Circuit Board (PCB) and controlled by an ALTERA Cyclone IV FPGA-based control board. The Schottky detector is arranged in a third PCB. The PCBs with two DUTs and a Schottky detector are fixed and aligned with a metallic box, which can be observed in Fig. 3.

A schematic diagram of the GAPD array board together with the FPGA control board is shown in Fig. 4. The GAPD array board contains the GAPD detector. In an attempt to reduce multi-scattering in the particle path, no packages are used and the naked die is wire bonded directly to the board. The board is then perforated under the chip. Moreover, the die of the GAPD detector is thinned down to 250 μm . The FPGA control board comprises an ALTERA Cyclone IV FPGA, an FTDI chip for data transmission, an EEPROM memory, a USB connector for communication with a pc and an Ethernet connector for communication with the TLU. A power system with different voltage regulators is used to power the components of the board. Two oscillators that generate clock signals at 12 MHz and 50 MHz are used by the FTDI chip and the FPGA, respectively. The data transmission between the GAPD array board and the FPGA control board is done through a flat fpc/ffc cable. The FPGAs are used to generate fast logic control signals (RST, INH, CLK1 and CLK2_m) and also to receive a number of pulses generated by the sensor. The generated pulses are stored in an FPGA internal FIFO which has a programmable capacity. The number of frames to be stored by the FIFO is selected depending on the delay between the real event and the trigger signal. Moreover, the FPGAs also handle the TLU control signals. One single FPGA could be used to control both GAPD arrays, but a solution based on two FPGAs has been chosen in this work. The FPGAs are not aligned with the GAPD arrays.

The GAPD detectors are operated in a gated acquisition mode, which means that the sensor is not always active. Short gated 'on' periods and long gated 'off' periods allow to reduce the probability to detect the fake hits [23]. However, a low duty cycle (i.e., $t_{\text{on}}/(t_{\text{on}} + t_{\text{off}})^{-1}$) also reduces the probability to detect the real

Fig. 3. Metallic box used to hold and align the two DUTs and the Schottky detector. The top layer corresponds to the first DUT, which can be seen wire bonded at the center.

hits. The duty cycle is programmable through the FPGA. An appropriate duty cycle is chosen to facilitate the detection of particle counts without seriously increasing the fake hit

Fig. 4. Schematic diagram of the FPGA control board together with the GAPD array board.

probability. During the gated 'off' periods of the sensor, the detector is read sequentially row by row.

To characterize the performance of the GAPD technology during the test beam, it is also necessary to determine, with a reference system, the tracks of the high energy particles with great accuracy. The resolution of the reference system should be higher than the expected intrinsic resolution of the DUT. This is usually achieved with beam telescopes, which are placed in the test beam setup together with the DUT. Thus, it is possible to measure the tracks of the particles and study the response of the DUT at the same time. In this work, an upgrade of the EUDET/AIDA beam telescope with six reference planes subdivided into two arms is used for this purpose. The telescope has a sensitive area of $5 \times 5 \text{ cm}^2$ and a spatial resolution around $4.5 \mu\text{m}$ per plane. The dies, together with the PCBs and the FPGAs, are placed inside an aluminum box to protect the sensors from uncontrolled light sources. The aluminum box, whose layers are $100 \mu\text{m}$ thick, is allocated between the two arms of the telescope. Remote-controlled stages help to spatially align the telescope with the DUT. Nevertheless, the sensitive area of the telescope is much higher than that of the DUT. As a consequence, another element is needed to discriminate between the hits that occur in the overlapped DUT–telescope area from those ones that occur outside this region. In this work, a Schottky detector [24] of 1 mm diameter and $300 \mu\text{m}$ thick is used. The Schottky detector is arranged in a PCB of 1.6 mm thick and placed between the two dies in the aluminum box.

A TLU [25] is used as an interface between the EUDET/AIDA telescope, the GAPD detectors and the data acquisition system. The TLU is operated under the trigger data handshake, in which data is transferred from the TLU to the FPGAs on each trigger. The TLU receives trigger signals from both the front and back arms of the telescope (one signal per arm) as well as the Schottky detector. The output nodes of these devices are connected to three different input channels of the TLU, which performs the logic AND of the three signals. Upon trigger coincidence between both arms of the telescope and the Schottky detector (i.e., the output of the logic gate AND is set to '1'), the TLU asserts the TRIGGER output signal. In response, the FPGAs force the TLU BUSY input signal to '1'. On receipt of the BUSY signal going high, the TLU de-asserts the TRIGGER signal and the FPGAs send 16 TRIGGER-CLOCK pulses. The pulses are counted by the TRIGGER line, whose pin has been switched to the output of a shift register holding the trigger number. Within the 16 TRIGGER-CLOCK pulses, the TLU sends the 16 bits of the time-stamp to the FPGAs. The time-stamp together with the current content of the FIFOs is

transferred to a computer via an FTDI chip and a USB cable. Simultaneously, six frames that correspond to the six arms of the telescope for the same time-stamp are stored in a second computer. This second computer is equipped with EUtelescope [26], the software of the EUDET/AIDA beam telescope. In the last place, when the writing data is complete, the BUSY signal is set low and the system is ready for triggers again.

4. Characterization of the setup

The software EUtelescope reconstructs the particle trace through six planes of the telescope with an intrinsic resolution between 2 and $3 \mu\text{m}$. The interpolation of this trace should allow to determine through which pixel of the DUT, or even through which specific area of a certain pixel, the particle has passed. However, the different materials of the test beam setup can introduce scattering phenomenon that deviate the particle path. As a consequence, the interpolation of a particular trace is affected by a certain degree of uncertainty. This uncertainty limits the reconstruction of the particle trace through the DUT. In the worst case, when there is a particle entrance but not an exit, it becomes impossible to determine which pixel of the DUT has been hit.

In order to determine, in advance, the expected extent of the multiscattering phenomenon, it is mandatory to simulate the passage of particles through the materials of the test beam setup. However, the complete response of a given semiconductor to an energetic electron beam is difficult to predict because of the many physical effects that can occur (probabilistic domain). Nevertheless, the Geant4 software (for Geometry And Tracking) [27,28], developed at CERN, can be used to predict all these interactions. Both the semiconductor geometry and thickness are key input parameters for Geant4. The amount of electron-hole pairs produced by incident electrons can be obtained using Monte Carlo simulations over the whole electron energy range. In this work, two setups have been studied. In the first case, the setup analyzed includes all the different materials that can introduce scattering in the particle path. These materials are two aluminum layers of $100 \mu\text{m}$ thick each (in gray in Fig. 5(a)), two GAPD detectors of $250 \mu\text{m}$ thick each (in orange in Fig. 5(a)), one Schottky detector of $300 \mu\text{m}$ thick (in yellow in Fig. 5(a)) and three PCBs of 1.6 mm thick each (in green in Fig. 5(b)). The two aluminum layers correspond to the front and back sides of the box in which the GAPDs and the Schottky detector are placed. The three PCBs correspond to the two GAPD detectors and the Schottky detector. The distance between each one of these

Fig. 5. Schematic diagram of the setup materials used in the Geant4 analysis, with complete (a) and simplified (b) versions. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Expected standard deviations of the hit distribution at DESY and CERN test beams.

Source	Electrons (6 GeV)		Pions (120 GeV)	
Distance ^a (cm)	2	10	2	10
Scattering of setup 3(a) (μm)	17.69	50.01	0.86	2.48
Scattering of setup 3(b) (μm)	9.37	26.02	0.45	1.23

^a The distance corresponds to the separation between the inner plane of the EUDET/AIDA telescope and the side of the box that contains the DUT.

elements is taken to be 1 cm. The blue layer of Fig. 5(a) corresponds to the first plane of the back arm of the beam telescope. Different distances of 2 cm and 10 cm between the back side of the box and the first plane of the back arm of the telescope have been simulated. In addition, to study the effects of the PCB and point out the importance of reducing the area of this material to the minimum, a second test beam setup, in which the PCBs have been removed, has also been characterized. The second test beam setup is depicted in Fig. 5(b).

The particles are launched from the front side of the test beam setup. For the analysis with Geant4, it has been considered that they are launched from a distance equal to the separation between the last plane of the front arm of the beam telescope and the front aluminum layer, which is either 2 or 10 cm in these simulations. The particles are launched with perpendicular momentum with reference to the aluminum layer. The particle sources are a 6 GeV electron beam at DESY and a 120 GeV pion beam at CERN.

The standard deviations of the hit distribution in the EUDET/AIDA beam telescope obtained with the simulations for the two proposed setups are presented in Table 1. As expected, the

deviation of the particle track increases with the distance between the inner plane of the telescope and the aluminum layer. It also increases with the presence of more materials in the setup. An intrinsic resolution of $9.37 \mu\text{m}$ can be achieved at DESY test beam with the simplified setup (Fig. 5(b)) and a telescope–aluminum layer separation of 2 cm. If the complete setup is used (Fig. 5(a)), the maximum achievable resolution is reduced down to $17.69 \mu\text{m}$. In addition, if the distance between the telescope–aluminum layer increases up to 10 cm, the maximum resolution will be $26.02 \mu\text{m}$ for the simplified setup and $50.01 \mu\text{m}$ for the complete one. These results outline the importance of reducing the amount of materials used in the test setup to minimum. Moreover, it is also clear that the telescope should be as near as possible to the aluminum box. However, given that the pixel width is $20 \mu\text{m}$, it should still be possible to distinguish detection at pixel level. In contrast, at CERN test beam with a telescope–aluminum layer distance of 2 cm the deviation is under $1 \mu\text{m}$ for both studied setups. When the telescope–aluminum layer separation is increased up to 10 cm, the particle deviation will be $1.23 \mu\text{m}$ and $2.48 \mu\text{m}$ for the simplified and complete setups, respectively. The experiment at CERN should allow to characterize the sensitive areas within a pixel. In particular, it should allow to determine the efficiency of the GAPD p-tub implantation (guard ring), as it has been previously suggested [29]. To sum up, we expect to characterize the efficiency of the sensor as a function of the position, the crosstalk, the spatial resolution and the two-track resolution. The measurements will be repeated for different overvoltages.

5. Conclusion

A setup for a GAPD detector test beam has been presented. The setup consists of two GAPD arrays, three PCBs, two ALTERA Cyclone IV FPGA-based control boards, a reference system consisting of one Schottky detector and an EUDET/AIDA beam telescope, and a TLU. The GAPD array has been designed and fabricated with a standard CMOS technology. The detector has $1 \times 1 \text{ mm}^2$ of sensitive area to fit the test beam requirements. In addition, it can be operated in a gated mode to reduce the probability to detect the intrinsic sensor noise. At present time, two test beams, at DESY with a 6 GeV electron beam and at CERN with a 120 GeV pion beam, are already planned. At the test beams, we expect to characterize the GAPD response to high energy particles. According to our analysis with Geant4, the benefits of minimizing the amount of materials used in the setup are significant, especially at DESY. It is also important to place the telescope as near as possible to the aluminum box that contains the DUT. With our setup, and according to our results with Geant4, we expect to characterize the GAPD response at pixel level at the DESY test beam and to study the different areas of sensitivity within a pixel at the CERN test beam.

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