Time-Resolved 3D Imaging with Capacitively Coupled GaAs SAM-APD and Cross-Delay Lines for Hard X-Ray Photon Detection

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***Abstract*—Time-resolved ultrafast phenomena with hard X-ray radiation are among the groundbreaking research fields underlying scientific applications like pump-and-probe spectroscopy. Research on detectors and studies of new multichannel acquisition techniques are continually driven by increasingly stringent requirements. This motivates our proposal of an innovative detector designed for a fully digital 3D (x-y-time) imager for hard X-rays. From the detector's perspective, the aspects in need of improvement include time resolution, spatial resolution (limited by the multipixel approach in most of the solutions), and quantum efficiency, particularly poor for silicon-based detectors in the case of hard X-rays. In this context, a Separate Absorption and Multiplication Avalanche PhotoDiode (SAM-APD) based on III-V semiconductors will be employed. Specifically, GaAs-based alloys feature a higher atomic number and mobility, making them much more efficient and faster than silicon in absorbing hard X-rays. Considering acquisition systems, the multichannel approach adopted by modern applications and the reduction of power and area budgets dedicated to individual channels shift the read-out electronics from the classical pixelated voltage-mode approach, involving analog waveform acquisition and digital processing, to time-based acquisition where both spatial (i.e., x and y) and timing information are tied to the time of the detection event. Temporal and spatial resolutions less than tens of picoseconds and hundred micrometers will be achieved by capacitive coupling of a large area (a few mm in diameter) GaAs SAM-APD to two Cross Delay-Lines (CDLs) connected to a 4-channel 15-ps precision FPGA-based Time-to-Digital-Converter (TDC). This presents a powerful alternative to pixelation from both a technological and a processing standpoint; notably, it requires no aggressive lithography and only four channels, as opposed to one per pixel.**

***Index Terms*—Hard X-rays detectors, GaAs-based avalanche photodiodes, Separate Absorption and Multiplication Avalanche PhotoDiode (SAM-APD), Cross Delay-Line (CDL), time-resolved experiments.**

I. SUMMARY

THE time and spatial resolution of hard X-ray photon detection systems are fundamental elements in many fields of physics and medical imaging, particularly in the study of transients in condensed matter [1] and in the radiative decay of molecules [2], just to mention the most common applications. Photon detectors based on compound semiconductors offer several advantages over traditional silicon sensors, including the availability of heavier materials providing substantially higher X-ray absorption and the possibility of tailoring their properties through bandgap engineering using techniques such as Molecular Beam Epitaxy (MBE). In particular, Separate Absorption and Multiplication region Avalanche Photodiodes (SAM-APDs) with variable-composition by III-V multilayers (e.g., GaAs/AlGaAs) serving as the multiplication region can be manufactured, forming a superlattice (SL) that shows a staircase profile in potential under reverse bias . Such profile enhances electron impact ionization to achieve high multiplication factors with low associated noise due to the reduced hole multiplication at the same time [3], [4].

This paper focuses on the design of a GaAs SAM-APD with a precisely measured mesa diameter of 5–10 mm, capacitivly coupled through a resistive layer with two orthogonal Cross-Delay Lines (CDLs), one for the x spatial coordinate and the other for the y spatial coordinate, both of the same diameter, connected, with a proper front-end electronics, to a 15-ps precision FPGA-based Time-to-Digital Converter (TDC) to enable 3D (x, y, t) high-resolution imaging [5], [6]. This is indeed a completely original solution compared to the pixel-based approaches proposed so far and it allows for a more relaxed structure in terms of electronics and power consumption at the same resolution. Indeed, it provides the possibility of obtaining 3D information with only 4 terminals, 2 per CDL on the x-axis and another 2 for the CDL on the y-axis. Therefore, in addition to the FPGA hosting the high-resolution TDC required for timestamp generation and x, y, t coordinate extraction, the front-end electronics consist only of 4, 1 per terminal, amplifiers followed by Constant Fraction Discriminators (CFDs), instead of the "sea of circuits" typical of pixel structures. Temporal and spatial resolutions less than tens of picoseconds and hundred micrometers can be achieved with this system.

A sketch of the proposed sensor identifying the main regions is reported in Fig. 1.

In this context, the detection of a hard X-ray photon (orange dot in Fig. 2) within the absorption region of the GaAs SAM-APD leads to the generation of an electron-hole pair (orange star in Fig. 2) that propagates towards the multiplication region (orange arrow in Fig. 2), thereby amplifying the current signal. This signal is subsequently deposited as an image charge on the CDLs (red shadow in Fig. 2). Being a monolithic detector,

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Manuscript received May 7, 2024. Authors are with the DEIB Politecnico di Milano, Elettra Sincrotrone Trieste, DIA Università di Trieste, Department of Physics University of Trieste, DPIA Università degli Studi di Udine, Università degli Studi di Modena e Reggio Emilia, INFN Trieste, and CNR-IOM, (nicola.lusardi@polimi.it).

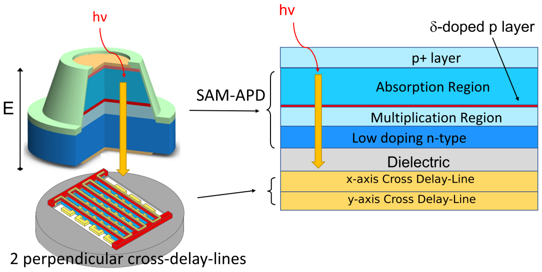

Fig. 1. GaAs SAM-APD with a single mesa and its related regions capacitively coupled with 2 orthogonal CDLs.

appropriate doping and proper sizing of the various regions allow not only to preserve the spatial coherence between the point of interaction of the incident hard X-ray photon with the detector and the generation of the image charge on the CDLs, but also to minimize the existing temporal jitter between these two events. In this sense, the time delay measured between the output signals in a CDL will be proportional to the spatial coordinate (i.e., x or y) of the detected photon, while the average between them represents the time-of-arrival of the hard X-ray photon.

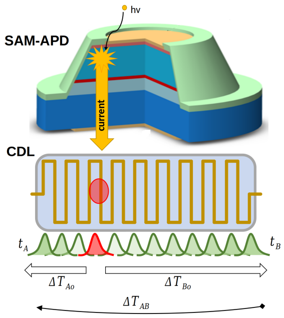

Fig. 2. Working principle of the proposed architecture (only one CDL is represented for simplicity).

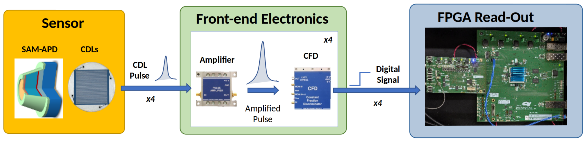

Fig. 3. Proposed sensor interfaced with front-end electronics and FPGA-based readout.

The GaAs SAM-APD detector is grown through MBE on an intrinsic GaAs semi-insulating substrate, and a resistivity of $10^8\,\Omega\cdot cm$ and a thickness of $500\,\mu m$, with a diameter of $2''$ (i.e., $50.8\,mm$). Subsequently, mesas of 5–10 mm of diameter are fabricated, which are then coupled with the CDLs [7].

As illustrated in Fig. 1, the GaAs SAM-APD consists of a GaAs $5-15\,\mu m$ p-i-p absorber (i.e., a p+ layer, Absorption Region, a δ-doped p layer) deposited on top of a $\sim 1\,\mu m$ p-i-n multiplication region (i.e., a δ-doped p layer, Multiplication Region, a low doping n-type layer). The δ-doped p layer consist of a single layer of carbons atoms with density planar $2.5\times10^{12}\,cm^{-2}$, which decouples the absorption and multiplication regions. The thicknesses of the various regions and their respective dopants are reported in Tab. I; these parameters gives the GaAs SAM-APD a breakdown voltage of ~38 V.

TABLE I
Name, thickness, material, and doping of the regions of the proposed GaAs SAM-APD.

Name	Thickness	Material	Dopant $[cm^{-3}]$
p+ layer	$150\,nm$	GaAs	C at 5×10^{18}
Absorption Region	$5-15\,\mu m$	GaAs	-
δ-doped p layer	1 atom	C	-
Multiplication Region	$1\,\mu m$	GaAs	-
Low-doping n-type layer	$2\,\mu m$	GaAs	Si at 1×10^{16}

It is important to emphasize that , differing from the standalone SAM-APDs developed in [7], the n-type contact layer must be able to sustain for the application of the reverse voltage necessary for photon detection, but not too highly doped nor thick, in order to limit lateral carrier diffusion that would degrade spatial resolution of the CDLs. When reverse-biased, the GaAs SAM-APD allows for the application of almost the entire reverse voltage to the Multiplication Region, thus generating a high electric field that facilitates the multiplication of the photocurrent generated in the Absorption Region, thus preserving its spatial and temporal coherence.

A graphical representation of the read-out scheme is shown in Fig. 3.

ACKNOWLEDGMENT

The work is supported by European Union – NextGenerationEU - PNRR M4.C2.1.1 - PRIN 2022 - Code 20227N9LW7 - CUP D53D23001040001, G53D23000350006, B53D23002300006, J53D23000610006, I53D23000220 006.

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