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3D-integrated sensors for particle physics detectors

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The goal of our project is to develop technology that enables large-scale particle detectors with 3D-integrated ASIC designs to achieve 10 µm position and 10 ps precision timing resolutions. The sensors used in this application are based on Low-gain avalanche diodes (LGADs), developed in a standard foundry CMOS process. We also developed a readout ASICs to match these sensors in the TSMC 28 nm CMOS process. Target performance is < 20 ps timing resolution, while maintaining the power consumption below 1 W/cm2. We will present the details of the designs and the results of the first measurements.

Summary (500 words)

I. INTRODUCTION

The overarching theme of this project is the development of 3D-integrated sensors that achieve 10 µm position resolution and 10 ps precision timing resolution. Highly granular precision timing detectors are required to achieve scientific breakthroughs across applications in High Energy Physics, Nuclear Physics, Basic Energy Research, and Fusion Energy Research, and their critical need was highlighted by DOE BRN, European Strategy for Particle Physics, and Snowmass. While some of the details of their technical requirements varies between applications across these disciplines, the need for extreme precision is shared.

The LGAD sensors are a leading candidate for such applications, and will be used in upgrades of the CMS and ATLAS experiments. We will present the project that develops the LGAD sensors on in commercial 12-inch wafer processes that can be cost-effectively 3D-integrated with readout ASICs 12”CMOS process.

II. BACKGROUND AND SIGNIFICANCE

The development of 3D-integrated radiation detectors represents a transformative step in advancing sensor technologies for both scientific and commercial applications. They offer key advantages over current technologies like SPADs in LIDAR systems, including operation in a linear gain regime and enhanced timing. Beyond LIDAR, time-of-flight applications such as mass spectrometry and TOF-PET can also benefit. This research also supports the broader scientific goals by facilitating basic research while enabling commercial scalability through partnerships with industry.

In high-energy and nuclear physics, precision detectors are increasingly essential. Future e^+e^- and multi-TeV colliders demand sensors with per-pixel timing near 10 ps and pixel sizes around 10 µm. These requirements call for high granularity detectors with low power consumption, compact TDCs, and memory components integrated within tight spatial constraints. Materials and chemical science experiments also require advanced detector capabilities, particularly for soft X-ray detection and high-speed imaging.

To realize these advancements, a critical technological leap lies in 3D-integration using wafer-to-wafer bonding, especially transitioning to 12”wafers for compatibility between LGAD sensors and 28 nm CMOS ASICs. This integration allows vertical stacking of circuitry, overcoming limitations in pixel area and bump-bonding constraints.

III. RESULTS

The prototype LGAD sensors have been designed and submitted to the foundry, and the first round of prototypes of the readout ASIC have been designed, produced and tested. The readout ASIC was developed in the 28 nm CMOS process, while the LGAD sensors are produced in TPSCo 65 nm node. Early measurements show these parameters are consistent with obtaining ˜15 ps timing precision. Detailed results of the ongoing chip testing will be presented.

IV. CONCLUSION

We designed and manufactured the LGAD sensors on 12”65 nm CMOS process, and the readout chip in TSMC 28 nm technology. Detailed results of the ongoing chip testing will be presented.

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