Applications of Low Gain Avalanche Detectors
4-Dimensional Tracking with Ultra-Fast Silicon Detectors

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Introduction

The measurement of trajectories of charged particles is ubiquitous in applications of physics to a wide variety of areas. This ranges from cosmic rays in space science to ionized molecules in mass spectrometers and charged particles in medical treatment, all the way to research on fundamental particle interactions in nuclear and particle physics. These applications using charged particles typically require measurements of particle locations to a specified accuracy, coverage of a specified detection area by a particle detector, and the ability to deal with a specified rate of incoming particle hits. However, improvements in rate capability often translate into more rapid measurements and larger amounts of data collected, providing an improvement in the capability of an apparatus. A crucial tool for making such particle measurements has been the silicon sensor. Given its relation to silicon technology through the planar fabrication process, it has allowed very high spatial granularity while covering large areas using arrays and providing the ability to accept data at very high rates when connected to appropriate Very Large Scale Integrated (VLSI) electronics. One constraint has been the signal formation process, which has traditionally limited the ability to measure the arrival time of a particle to greater than 0.2 ns. Based on the speed of light, this corresponds to more than 5 cm of flight path uncertainty if we use the device to measure flight distances.

The recent development of a new type of silicon sensor promises to significantly enhance the capability to measure track arrival times, which will dramatically improve the capability of silicon arrays. The goal is to simultaneously maintain the high granularity for spatial measurement and the high data rate collection capability, while also making precise time measurements. The time measurement requires very short duration signals, which allow larger data rates than those possible from conventional silicon sensors. An array of these detectors can cover a large detection area like the more traditional silicon detectors. Assuming an arrival time accuracy of 10 ps, it would reduce the flight path length measurement uncertainty of relativistic particles to 3 mm. Such precise time measurement can also be used for other purposes: For example, it can be used to group particles simultaneously coming from a well-defined location by their common arrival time if they are moving at relativistic speeds. This can be very useful at particle colliders if many interactions are occurring reasonably close in time but are resolvable by a 10 ps time measurement. Beyond HEP, another application of this type of silicon sensor is for x-ray diffraction experiments in the few keV range. In this type of experiment, the internal gain of the LGAD multiplies the charge deposited by the x-ray to boost the signal-to-noise ratio.

Development of Ultra-Fast Silicon Detectors (UFSD)

Charge multiplication is well understood in gases and solids and is based on the avalanche process initiated by a charge moving in large electrical fields. This leads to impact ionization with a gain given by the average number of final particles created by one particle. In semiconductors, this effect is used in Avalanche Photon Detectors (APD) with gain in the 100's and in Silicon Photon Multipliers (SiPM) with a gain of about 10,000. In contrast to those applications, Ultra-Fast Silicon Detectors (UFSD) are based on Low-Gain Avalanche Detectors (LGAD) with a gain of ~20. LGAD design is based on a modification of the doping profile in which an additional doping layer of p^+ material (Boron or Gallium) is introduced close to the n-p junction in an n-in-p sensor. The resulting doping profile is characterized by a large increase in doping concentration near the junction, in turn creating a large electric field. The electric field in LGAD is thus divided into two distinct zones: the drift volume with rather low electric field values (E ~ 30kV/cm), and a thin multiplication zone within a depth of a few micrometers with very high field (E ~ 300kV/cm). The implants need to be shaped to allow high bias-voltage operation without breaking down. In the n-in-p LGAD design, electrons drift toward the n^{++} electrode to initiate the multiplication process. Since the multiplication mechanism starts for electrons at a lower electric field than what is necessary for hole multiplication, the n-in-p design offers the best control over the multiplication process. In fact, it is possible in the n-in-p design to adjust the value of the electric field so that only electrons drive the multiplication process and operating the device in avalanche mode is avoided. Under such conditions the gain is not that sensitive to the exact value of the detector voltage and the LGAD can be operated reliably. This condition also minimizes the noise coming from the multiplication process, known as the “excess noise factor”, enhancing the LGAD performance.

The Santa Cruz Institute for Particle Physics (SCIPP) at the University of California Santa Cruz (UCSC) has been collaborating with three LGAD manufacturers—Hamamatsu Photonics (HPK) in Japan, Centro Nacional de Microelectrónica (CNM) in Spain, and Fondazione Bruno Kessler (FBK) in Italy—to develop various sensors. During the past two years, the basic operations of LGAD devices have been demonstrated by the SCIPP team through several beam tests and laboratory measurements. In June 2016, three 45 μm thick LGAD manufactured by CNM were tested in a 180 GeV/c pion beam at CERN [1]. These measurements established that a time resolution better than 30 ps can be achieved with silicon sensors, and that the time resolution of several LGAD improves with the inverse of the square root of the number of sensors.

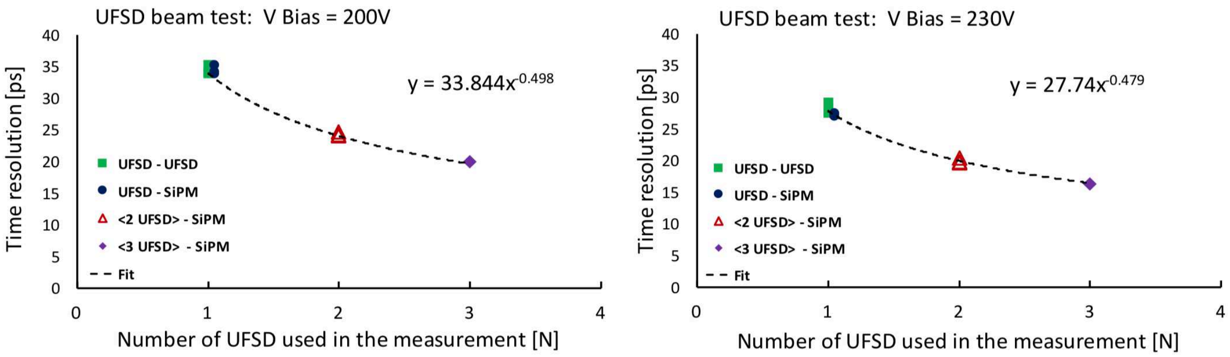

Fig. 1: Timing resolution for single UFSD (N=1) obtained from the UFSD-SiPM and UFSD-UFSD time differences, averaged pairs of UFSD (N=2) and average of 3 UFSD (N=3) for bias voltages of 200V (left) and 230V (right) [1].

The radiation performance of the LGAD was also tested using the SCIPP electron telescope. In a comprehensive study using HPK sensors irradiated with neutrons up to 6e15 n/cm^2, the internal gain and time resolution were measured, the results of which were recently published in a paper that I am an author on [2]. In Figure 2, the bias voltage and the time resolution at a Constant Fraction Discriminator (CFD) setting of 30% are shown as a function of neutron fluence.

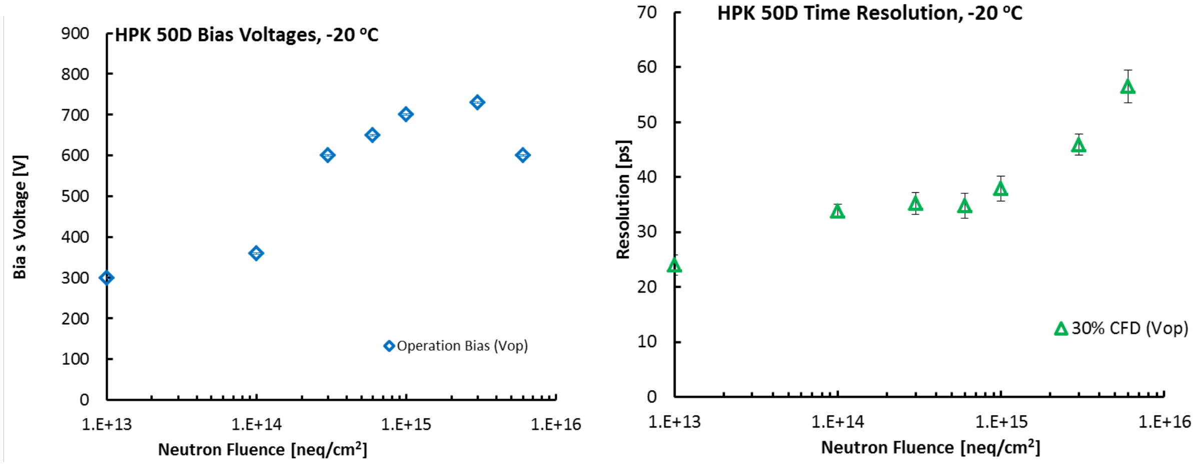

Fig. 2: Bias Voltage and time resolution at CFD threshold of 30% as a function of neutron fluence.

The data conclusively show that as fluence increases, the required bias also increases since the doping density in the multiplication layer decreases through the acceptor removal process. The higher field due to the increased bias partially compensates for the doping loss. The time resolution is better than 40 ps up to a fluence of 1e15 n/cm^2 and below 55 ps at 6e15 n/cm^2, satisfying the requirements for applications at the High Luminosity- Large Hadron Collider (HL-LHC), the first large-scale application of UFSD that we envision, described below.

Further Technological Development of LGAD

We are looking forward to further optimizing HPK, CNM, and FBK LGAD technology in early 2018. Based on our measurements, we have recommended separate batches for reduced inter-pad distance, reduced edge space, shallower p-doping profile, variation in doping density, and two thicknesses of 50 µm and 35 µm. We plan to test the different batches, including radiation testing, for which we believe we have developed a methodology tailored to the needs of future experiments. This includes I-V, C-V, charge collection, and timing studies. HPK already produced the first 35 µm thick LGAD prototypes, which show promising performance, including improved timing resolution, lower bias voltage, and reduced leakage current.

In addition, radiation hardening will proceed with mitigation of the acceptor removal, on the one hand by replacing Boron with Gallium, and on the other hand by diffusing carbon into the multiplication layer. Both of these will be prototyped in 2018.

In addition, pixelated LGAD are being manufactured in a new type of AC-LGAD, characterized by unsegmented sheets of the p-multiplication layer, the n-implant and a coupling oxide with a segmented metal contact on top so that the signal is AC coupled. AC-LGAD will allow improved simultaneous measurements of deposited energy, position, and time. This concept also promises a much-simplified design and simplified manufacturing, and more robust operation than the current fully segmented LGAD. The first prototypes have been shown to work and the next generation is being fabricated by CNM. I plan to collaborate with Argonne National Lab Physicist Dr. Jessica Metcalfe to test the performance of these novel detectors at the ANL light source.

LGAD Applications

The very forward region at the HL-LHC is very challenging to deal with since a fixed rapidity interval corresponds to a physically compressed area. The production of particles per unit area grows as $1/r^2$ as a function of the radial distance from the beam line. To improve the rejection of pileup, both ATLAS and CMS are planning to build special timing detectors in the endcap region using LGAD. The ATLAS device is known as the High Granularity Timing Detector (HGTD). The High Granularity Timing Detector (one on each side of ATLAS) will be located just outside the silicon tracking system and directly in front of the end-cap cryostats about 3.5 m away from the interaction region. The goal is to group particle hits by time, which will allow selection of particles from the same interaction that have the same arrival time. Since pile-up jets have particles scattered in time, improved rejection of pile-up jets will be possible which is necessary since the ATLAS calorimeters cannot distinguish this. The ATLAS High Granularity Timing Detector will cover a rapidity from about 2.4 to 4.0 and will see approximately 12,000 hits per crossing, arriving in a 1 nanosecond interval, although the greatest density of hits will arrive in about half that time. To maintain a sufficiently low occupancy, the silicon detectors are arranged as pads approximately 1.3mm^2. A significant amount of R&D is required to be able to build these timing detectors, much of it directly planned as part of this proposal. A time-line is outlined as follows:

In 2018, we will have a combined ATLAS/CMS run at HPK where we will concentrate on producing full-size wafers for ASIC and module development. Many of the optimizations mentioned earlier will be implemented in full-size detectors in a second run in 2019 which will lead to a pre-production run in 2021.

Qualifications, Collaboration, and Resources

The R&D for the ATLAS HGTD is planned for 2018-2020. Since I completed my written qualifying exams at the beginning of this quarter and will finish my coursework at the end of this quarter, I am looking forward to full-time HGTD R&D planned for 2018-2020. In the past year, I have been involved in all aspects of UCSC's timing detector research. This includes both Monte Carlo simulation necessary for designing the proposed timing detector, as well as testing the new silicon sensors in the lab to determine their electrical properties and how they will respond to radiation at the HL-LHC. In the coming years we will be receiving an increasingly large number of sensors from our manufacturers, so I will work in the lab with the knowledge and skills I have gained to test their properties in order to optimize the radiation hardness and timing resolution for LGAD. I will continue to collect sensor data from beam tests, TCT laser, and the beta telescope to compare different manufacturers and different LGAD designs, improve our understanding of the multiplication process and the radiation effects, and work on optimizing the design of large arrays and the simplified AC-LGAD design.

Optimizing the design of large arrays will be challenging because the breakdown voltage has varied significantly for the 4x4 and 8x8 arrays tested already, even with consistent measurements for single pads. Proximity to the guard ring around the active area seems to have some effect on breakdown voltage, though the complete effects are not well understood yet. Therefore, studying the limits of the detectors to expand it to 1,000 pads measuring uniformly will be a challenging, yet necessary step. In conjunction with the experimental data, I will use the silicon detector simulation program “Weightfield2” to study the guard ring effects.

As UCSC is the leading institution worldwide in testing and designing the sensors for the ATLAS HGTD, I will have access to silicon detector cleanroom facilities and great mentorship from silicon detector experts Professors Abraham Seiden and Hartmut Sadrozinski. We have also built strong collaborations with SLAC, Fermilab, and Brookhaven National Labs during beam tests and sensor development.

In addition, we are beginning to collaborate with Argonne National Lab Physicist Dr. Jessica Metcalfe who is an expert on Silicon Pixel Detectors. I plan to collaborate with her group to use the ANL light source to gauge the detection of x-rays with our novel AC-LGAD, including radiation damage effects. Her group is currently conducting research on crystalline fast timing detectors, and the materials science and electron microscopy perspective on radiation damage will contribute valuable insight to our LGAD research.

Broader Impacts

The internal gain improvements in this new LGAD silicon technology will also be useful for applications to various other types of detectors, such as for different particle physics experiments and medical imaging. For example, improved precision in time measurements is essential for proton computed tomography (pCT) cancer treatment to measure residual proton energy to limit radiation exposure to healthy cells [3]. Communicating this technology as something relevant to our collaborators, colleagues, and the general public through outreach is part of our role as scientists. We have already begun publishing the results for others to use.

Furthermore, the UCSC ATLAS group is part of the SCIPP, which is dedicated to improving physics education and accessibility on campus and in the local community. SCIPP is a host for QuarkNet, a program aimed at introducing particle physics in high school classrooms. Local high school students and teachers come to UCSC to learn about the goals and tools used for particle physics. I was a QuarkNet mentor this past spring, so using my extensive mentoring and teaching experiences I plan to dedicate a substantial amount of time to outreach in the coming years through SCIPP and UCSC's Women in Physics and Astronomy (WiPA) group. This year I am WiPA's co-outreach coordinator. In this role, I organize and run a variety of activities and demos to help younger scientists of middle and high school age, especially women and other underrepresented minorities, gain the same sense of discovery and passion from doing science labs that I have been fortunate enough to experience. In addition to coordinating outreach activities, I will participate in the Matriculating, Influencing, Networking and Triumphing (MINT) Program at the UCSC Women's Center by exhibiting SCIPP's research to recruit underrepresented students to work in our labs. The wide variety of tasks of my project will be a perfect place to introduce students to our group's cutting-edge silicon detector research.

References

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