Liquid Argon Skipper Charge-Coupled Detector (LAr-CCD): Fusing Semiconductor Precision and Noble Liquid Scaling for Next-Generation HEP Detectors

Introduction

High energy physics experiments demand new detector technologies capable of unprecedented sensitivity while maintaining robust performance in extreme environments. Liquid argon (LAr) time projection chambers (TPCs) have become a mainstay in neutrino and rare-event physics due to their excellent ionization yield, scalability, and 3D imaging capabilities [1,2]. However, a persistent bottleneck remains: the efficient collection, transfer, and readout of ionization electrons, especially at the poorly understood interface physics between the noble liquid and solid-state electronics [3]. Losses at this interface, due to charge trapping, recombination, and field inhomogeneities, fundamentally limit the energy resolution and sensitivity of current detectors needed for probing elusive interactions or high energy particles of interest [4].

Charge-coupled devices (CCDs) have revolutionized imaging and low-background detection in solid-state physics, achieving exquisite charge transfer efficiency through engineered potential wells and clocked gate structures [5]. In addition, an advanced form of CCDs are skipper CCDs, which allow for multiple, non-destructive measurements of the same charge packet and represent a breakthrough in charge detection [6]. This architecture achieves sub-electron readout noise by averaging multiple independent measurements, a capability that has been experimentally demonstrated to reach noise levels below 0.2 electrons RMS per pixel [6]. Such ultra-low-noise performance is transformative for rare-event searches and low-background experiments, as it allows for the direct counting of individual electrons with unprecedented precision [7]. The ability to dynamically configure the number of readout samples per pixel provides flexibility to balance sensitivity and readout speed, making skipper CCDs highly attractive for applications in dark matter, neutrino detection, and quantum imaging [8].

However, incorporating these technologies to cryogenic noble liquids presents unexplored challenges in materials integration, interface quality, and charge transport physics. The LAr/Al_2O_3 interface presents unique challenges due to the liquid-solid boundary and cryogenic operating conditions. Recent work by the Oscura collaboration on skipper-CCDs has revealed that trap characteristics are more closely linked to fabrication processes than specific treatment methods, emphasizing the importance of systematic interface characterization [9]. Previous attempts to create charge transfer devices in noble liquids have focused primarily on dual-phase systems with gas multiplication [10]. The proposed approach represents a fundamentally different paradigm where charge transfer occurs entirely within the liquid phase, eliminating the complexity and instability associated with liquid-gas interfaces while enabling potentially enhanced charge transfer efficiency [10]. Building on these advances, the adaptation of skipper CCD and fabrication principles to cryogenic noble liquids may offer a transformative path forward for next-generation particle detectors.

Motivation and Prior Art

The LAr/Al_2O_3 interface is the critical mediator between the electric fields generated by the gate electrodes and the mobile charges in LAr. Achieving low interface trap densities (Dit < 10^{11} $cm^{-2}eV^{-1}$) is essential for minimizing charge loss and maximizing transfer efficiency [11]. A better understanding of the wetting or non-wetting at this interface may reveal design opportunities for ensuring consistent electric field penetration and engineering for predictable charge manipulation relevant for high energy physics experiments [12]. The proposed LAr skipper CCD detector directly addresses these limitations by applying atomic layer deposition techniques to achieve interface trap densities below 10^{10} $cm^{-2}eV^{-1}$, potentially improving charge collection efficiency by orders of magnitude [13].

While traditional CCDs convert light photons into electric signals, this device detects ionization events in LAr. The detector employs a layered architecture consisting of a silicon substrate base, silicon dioxide as a dielectric, aluminum metal gate electrodes, a 50 nm aluminum oxide (Al_2O_3) layer deposited via atomic layer deposition (ALD), and liquid argon as the detection medium seen in Figure 1. The detector operates in theory by creating and manipulating electrostatic potential wells within the liquid argon using an array of metal gate electrodes separated from the LAr by a precisely controlled ALD Al_2O_3 dielectric [5]. When a particle interaction occurs in the LAr, the resulting ionization electrons are drifted toward the Al_2O_3 interface due to an externally applied electric field [4]. These ionization electrons are confined in engineered wells, then laterally transferred and readout using clocked gate voltages, closely mimicking the operation of traditional CCDs but within a fundamentally different detection medium [14]. When a potential is applied to a gate electrode, the resulting electric field across the Al_2O_3 dielectric induces an electrostatic potential well in the adjacent liquid argon, attracting and confining mobile electrons [5,16]. By modulating the potentials on adjacent electrodes, you create penetrating electric fringing fields that allow for controlled lateral charge transfer between wells [5]. The success of this approach depends critically on the quality of the LAr/Al_2O_3 interface, as this boundary mediates the coupling between the electric fields generated by the gate electrodes and the charges within the liquid argon [4,9,11].

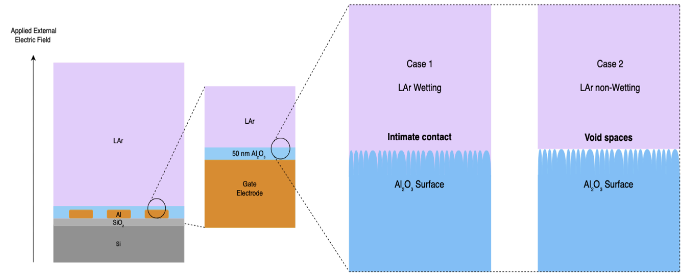

Figure 1. Architecture of the proposed skipper LAr-CCD detector and close up of the LAr/Al_2O_3 interface with two different possible cases for interface behavior.

Research on CCD gate oxides confirms that there exists an optimal thickness range for maintaining both electrical performance and reliability, with 50 nm falling within this optimized range for cryogenic liquid applications [17]. The mechanical stress from thermal contraction is manageable at this thickness, avoiding cracking or delamination issues that could occur with thicker films [18]. Although, ALD is considered the gold standard for producing high quality thin films, we can expect there to be some surface roughness resulting in void spaces [15]. This difference in contact will have an effect on the efficiency of charge transfer [16].

Specific Aims:

1) Characterize and optimize the LAr/Al_2O_3 interface by systematically measuring interface and border trap densities, performing hysteresis and multifrequency C−V analysis, and correlating these results with ALD process parameters to minimize charge trapping and maximize transfer efficiency.
2) Develop and demonstrate a proof-of-concept LAr-CCD device capable of controlled charge confinement and lateral transfer in liquid argon by engineering a prototype with optimized gate structures and validating its operation.
3) Demonstrate robust lateral charge transfer and low-noise readout at 87K and integrating synchronized readout electronics to validate device performance under realistic cryogenic detector conditions.

Timeline and Milestones

Year 1:

- Months 1-3: Al_2O_3 design optimization and fabrication of initial prototypes
- Months 4-6: Interface optimization and systematic C-V characterization
- Months 7-9: Cryogenic test system development and initial characterization
- Months 10-12: First publication submission

Year 2:

- Months 13-16: Advanced optimization and scaling studies
- Months 17-21: Integration with readout electronics and performance benchmarking
- Months 22-24: Second publication submission

References

[1] CPAD Detector R&D Roadmap, "Advanced Detector Technologies for HEP," https://cpad-dpf.org(2022)

[2] A. Marchionni, "Liquid argon time projection chambers," Annual Review of Nuclear and Particle Science 70, 477 (2020)

[3] Pereverzev, S. (2022). "What surfaces in the operation of noble liquids dark matter detectors." arXiv:2212.12969

[4] Boyle, G.J., et al. (2025). "Review of the experimental and theoretical landscape of electron transport in noble liquids." Frontiers in Detector Science and Technology

[5] Janesick, J. R. Scientific Charge-Coupled Devices; SPIE Press: Bellingham, WA, 2001.

[6] Fernández Moroni, G.; Estrada, J.; Cancelo, G.; Holland, S.; Paolini, E.; Volpe, G. Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon. Exp. Astron. 2012, 34, 43–64.

[7] Botti, A. M.; Cababié, M.; Estrada, J.; Fernández-Moroni, G.; Sofo Haro, M.; Tiffenberg, J. Sub-GeV dark matter and neutrino searches with Skipper-CCDs: status and prospects. PoS ICRC2021 2021, 505. https://www.osti.gov/biblio/1839558

[8] Cervantes-Vergara, B. A.; Perez, S.; D'Olivo, J. C.; Estrada, J.; Grimm, D. J.; Holland, S.; Sofo-Haro, M.; Wong, W. Skipper-CCDs: Current applications and future. Nucl. Instrum. Methods Phys. Res., Sect. A 2023, 1042, 167681. https://doi.org/10.1016/j.nima.2022.167681

[9] Oscura Collaboration, Perez, S. E.; Cervantes-Vergara, B. A.; Estrada, J.; Holland, S.; Rodrigues, D. P.; Tiffenberg, J. Studying single-electron traps in newly fabricated Skipper-CCDs for the Oscura experiment using the pocket-pumping technique. J. Appl. Phys.2024, 136, 204502. https://doi.org/10.1063/5.0170917

[10] Lux, T. Charge and Light Production in the Charge Readout System of a Dual Phase LAr TPC. arXiv 2018, arXiv:1812.08700.
[11] Rahman, M. M.; Shin, K.-Y.; Kim, T.-W. Characterization of Electrical Traps Formed in Al_2O_3 under Various ALD Conditions. Materials 2020, 13 (24), 5792.
[12] Li, J.; Wang, S.; Jiang, L. Fundamentals and Applications of Surface Wetting. Langmuir 2024, 40, 15, 7976–7997
[13] Felix, J. A.; Xiong, H. D.; Fleetwood, D. M.; Gusev, E. P.; Schrimpf, R. D.; Sternberg, A. L.; D'Emic, C. Interface trapping properties of nMOSFETs with $Al_2O_3/SiO_xN_y/Si(100)$ gate dielectric stacks after exposure to ionizing radiation. Microelectron. Eng. 2004, 72, 283–288.
[14] Marchionni, A. Liquid argon time projection chambers. Annu. Rev. Nucl. Part. Sci. 2020, 70, 477–500.
[15] George, S. M. Atomic Layer Deposition: An Overview. Chem. Rev. 2010, 110, 111–131. https://doi.org/10.1021/cr900056b
[16] Yan, D.; Lu, H.; Chen, D.; Zhang, R.; Zheng, Y.; Qian, X.; Li, A. Distribution of deep-level traps at atomic-layer-deposited Al_2O_3/n-GaN interface. Appl. Surf. Sci. 2012, 258, 4160–4164. https://doi.org/10.1016/j.apsusc.2011.12.025
[17] Kim, H.; Lee, H. B. R.; Maeng, W. Applications of atomic layer deposition to nanofabrication and emerging nanodevices. Thin Solid Films 2009, 517, 2563–2580. https://doi.org/10.1016/j.tsf.2008.10.005
[18] Ylivaara, O. M. E.; Langner, A.; Ek, S.; Malm, J.; Julin, J.; Laitinen, M.; Ali, S.; Sintonen, S.; Lipsanen, H.; Sajavaara, T.; Puurunen, R. L. Thermomechanical properties of aluminum oxide thin films made by atomic layer deposition. J. Vac. Sci. Technol. A2022, 40, 062414. https://doi.org/10.1116/6.0002095