Version 4

1) Charge-Coupled Device (CCD) Inspired Operation and Design Adapted for Cryogenic Liquid Argon Detector Technologies
2) Liquid Argon Charge-Coupled Device (LAr-CCD): Fusing Semiconductor Precision and Noble Liquid Scaling for Next-Generation HEP Detectors
3) CCD-Inspired Operation and Skipper Readout for Cryogenic Liquid Argon Detectors
4) Interface-Engineered LAr-CCD: Transforming Charge Readout in Noble Liquid 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 cutting-edge applications in dark matter, neutrino detection, and quantum imaging [8].

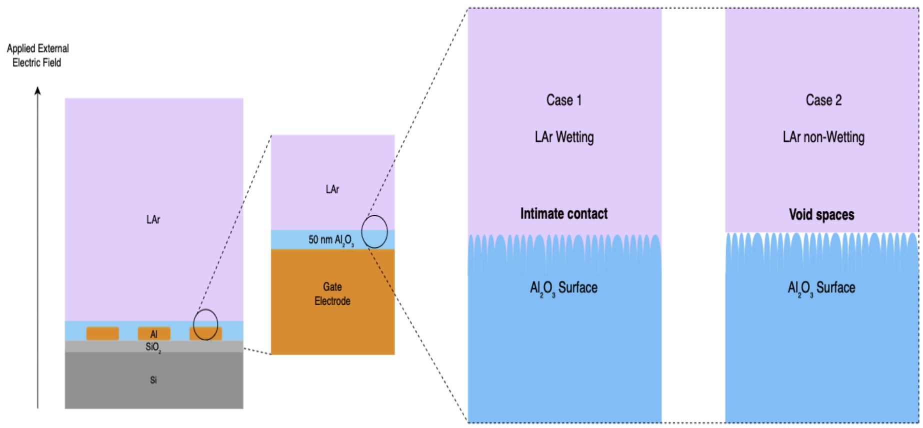
However, incorporating these technologies to cryogenic noble liquids presents unexplored challenges in materials integration, interface quality, and charge transport physics. The LAr/Al_2O_3 interface presents unique challenges due to the liquid-solid boundary and cryogenic operating conditions. Recent 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 superior charge transfer efficiency [10]. Building on these advances, the adaptation of CCD, 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 as can be seen in Figure 1. The detector operates in theory by creating and manipulating 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. 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. 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. When a potential is applied to one gate electrode, capacitive coupling generates a “potential well” in the LAr that attracts and confines negative charges. By modulating the potentials on adjacent electrodes, you create penetrating electric fringing fields that allow for controlled lateral charge transfer between wells. 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.

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.



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. This difference in contact will have an effect on the efficiency of charge transfer. 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. The mechanical stress from thermal contraction is manageable at this thickness, avoiding cracking or delamination issues that could occur with thicker films. The 50 nm Al_2O_3 thickness thus represents a carefully optimized choice that balances electrical performance, reliability, manufacturability, and providing the necessary capacitive coupling while maintaining robust breakdown characteristics under cryogenic operating conditions.

Deliverables

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5) Liquid Argon Charge-Coupled Device (LAr-CCD): Transforming Charge Readout in Noble Liquid Detectors
    - High-Fidelity Charge Manipulation in Liquid Argon: A CCD-Inspired Approach
    - Interface-Driven Charge Transfer: Advancing Noble Liquid Detector Readout

Project Title
Introduction
Objectives
- Develop a proof-of-concept LAr-CCD device for charge manipulation in LAr.
- Characterize the LAr/Al_2O_3 interface and optimize trap density.
- Demonstrate lateral charge transfer and readout at cryogenic temperatures.
Background and Motivation
Methods
- Design and fabrication of ALD structures.
- Interface characterization (Dit, breakdown, leakage).
- Charge transfer experiments in LAr.
Expected Impact
- Improved charge transfer efficiency.
- Lower noise and higher resolution than current readouts.
Risk Assessment
- Material compatibility
- Operation at cryogenic temperatures
- Interface stability
Timeline and Milestones
References