Version 3

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) 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

## Introduction

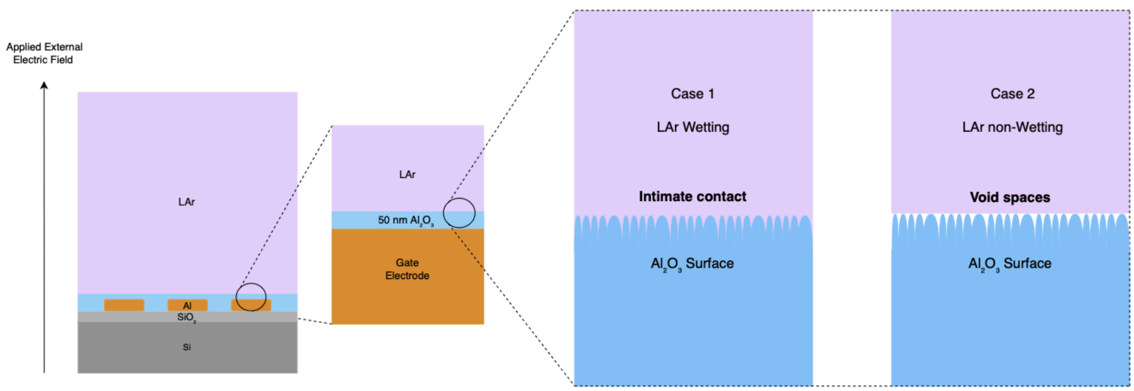
High energy physics experiments demand new detector technologies capable of unprecedented sensitivity while maintaining robust performance in extreme environments. Liquid argon (LAr) time projection chambers (TPCs) have become a mainstay in neutrino and rare-event physics due to their excellent ionization 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 sub-electron noise and exquisite charge transfer efficiency through engineered potential wells and clocked gate structures [ 5,6 ]. The adaptation of CCD principles to cryogenic noble liquids may offer a transformative path forward.

## Motivation and Prior Art

In this proposed inspired fusion, the LAr-CCD operates 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 atomic layer deposited (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 and 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 medium.

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 [7]. 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 [8].

**LAr-CCD Detector**




The proposed detector layered architecture consists of a silicon substrate base, 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. There is an external electric field being applied to this detector so if ionization in LAr creates free electrons they will drift towards the $Al_2O_3$ surface/interface.

**References**

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https://academicprogramsonline.org/ajo/award/29886

https://cpad-dpf.org/?page_id=285

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# 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

The LAr-CCD concept bridges the gap between semiconductor device physics and noble liquid detector technology, offering a platform for single-electron sensitivity, low-noise readout, and potentially pixelated imaging in large-scale LAr detectors. This approach directly addresses priorities identified by the Coordinating Panel for Advanced Detectors (CPAD), including the need for transformative instrumentation and improved charge readout in noble element detectors. By systematically investigating the operation, interface physics, and characterization of the LAr-CCD, this research aims to establish the foundational principles for a new class of detectors with broad applicability in neutrino, dark matter, and rare-event searches.

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. The 50 nm $Al_2O_3$ thickness balances electrical performance, reliability, manufacturability, and providing the necessary capacitive coupling while maintaining robust breakdown characteristics under cryogenic operating conditions. The silicon's main role is to to provide mechanical integrity