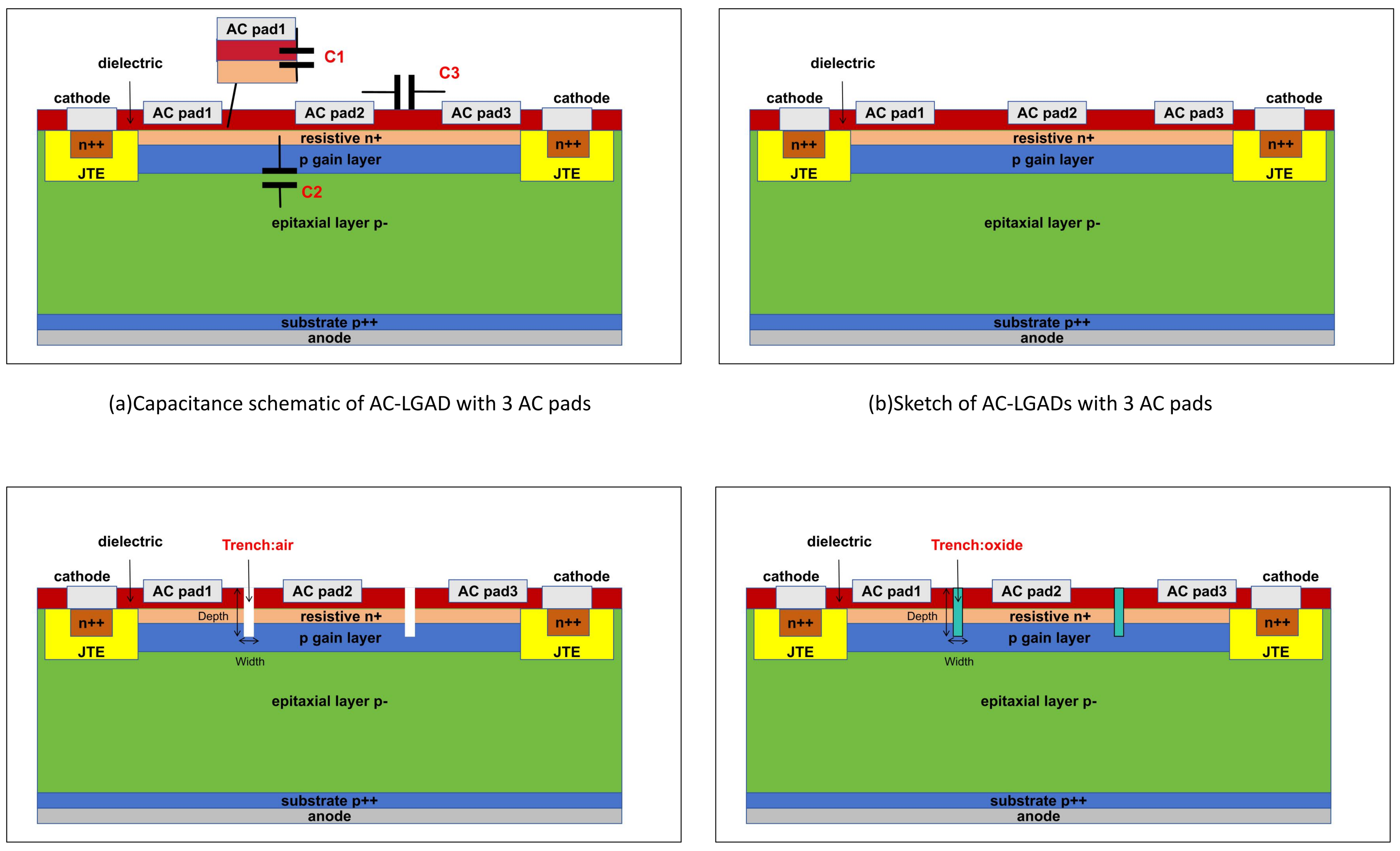
Capacitance Optimization of AC-LGAD Sensors through Novel Structure Design and TCAD Simulation

Xu Huang[1,*], Mei Zhao[2,5], Tianya Wu[1], Chaoyi Ke[2], Xiaoxu Zhang[3], Lei Zhang[3], Wenhao Huang[2], Huachuang Wang[4]

[1]Nanchang University, Nanchang, China [2]Insitute of High Energy Physics,CAS,Beijing, China [3]Nanjing University, Nanjing, China
[4]Harbin Engineering University, Harbin, China [5]Center for High Energy Physics，Henan Academy of Sciences China
*Contact Email: (Xu Huang) xuhuang.ncu@qq.com



(a)Capacitance schematic of AC-LGAD with 3 AC pads (b)Sketch of AC-LGADs with 3 AC pads

(c)Schematic of AC-LGADs with 3 AC pads and oxide-gap isolation (d)Schematic of AC-LGADs with 3 AC pads and air-gap isolation

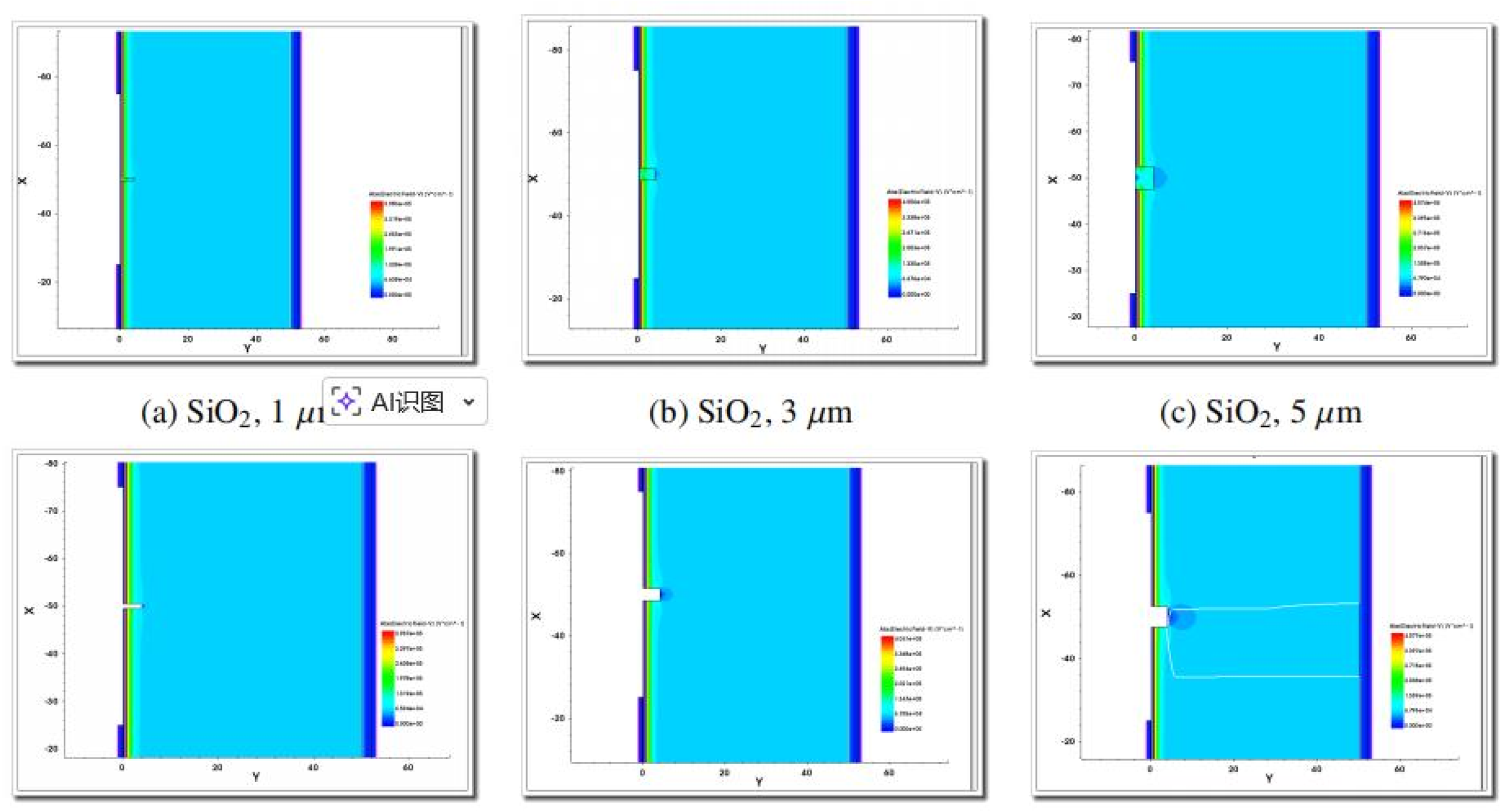
Fig. 1 Schematic diagrams of AC-LGAD structures: (a) Capacitance schematic (b) traditional structure, (c) with air-gap isolation, and (d) with oxide-gap isolation

Novel Low-Capacitance AC-LGAD Design: Core Innovations

- **Low-k Dielectric Isolation**
  - Method: Add trenches (filled with SiO_2 or air) between resistive electrodes.
  - Effect: Low-k materials cut electric field coupling, reducing $C_{\text{inter-pad}}$ by decreases by more than three orders of magnitude.
  - Outcome: Minimizes crosstalk, enhances spatial resolution.
- **Optimized Isolation Geometry**
  - Method: Tune isolation structure depth/width via simulations.
  - Effect: Deeper trenches concentrate electric fields; optimized width balances isolation & compactness.
  - Outcome: Ideal capacitance reduction, maintains practical sensor dimensions.

Electric Field Distribution Analysis

- Setup: 4 μm Depth, 0–10 μm Widths for Electric Field Distribution Study
- For the isolation width, both 1 μm and 3 μm are fully depleted



(a) SiO_2, 1 μm (b) SiO_2, 3 μm (c) SiO_2, 5 μm

(d) Air, 1 μm (e) Air, 3 μm (f) Air, 5 μm

Fig. 4 Electric Field Distributions: Isolation Structures' Effect

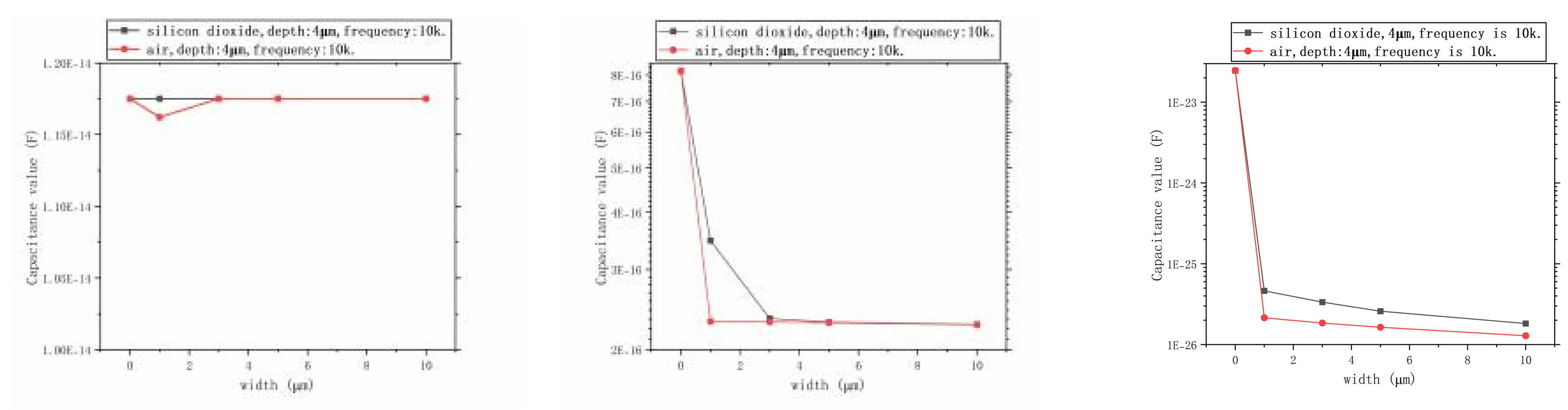
Summary

This work presents a Isolated-Structure low-capacitance AC-LGAD structure utilizing low-k dielectric isolation and optimized geometry. TCAD simulations demonstrate significant capacitance reduction:Bulk capacitance decreased to one strip capacitance, while inter-pad capacitance decreases by over three orders of magnitude with increasing isolation width(0-10 μ m).For same trench size parameters, Air isolation outperforms SiO2, providing 30% additional reduction in inter-pad capacitance.

Key Parasitic Capacitances in AC-LGAD Sensors

- **C1 (Coupling Capacitance, C_{coupling})**
  - Location: Metal readout strips ↔ semiconductor gain layer (across dielectric)
  - Impact: Weakens signal, slows rise time, distorts waveform
  - Dependence: Dielectric thickness, permittivity, effective area
- **C2 (Bulk Capacitance, C_{bulk})**
  - Location: p–n junction (n gain layer ↔ p+ gain layer with the p- epitaxial layer; space charge region as capacitor)
  - Impact: Forms low-pass filter (with front-end capacitance) → attenuates high-frequency signals, degrades timing precision
  - Dependence: Follows $C = \frac{\epsilon S}{d}$; relies on gain layer/backplane area, separation, medium permittivity
- **C3 (Inter-Pad Capacitance, $C_{\text{inter-pad}}$)**
  - Location: Adjacent resistive electrodes (via semiconductor bulk, from inter-electrode electric fields)
  - Impact: Causes crosstalk → interferes with position reconstruction, limits spatial resolution
  - Dependence: Electrode spacing, semiconductor permittivity, thickness under electrodes

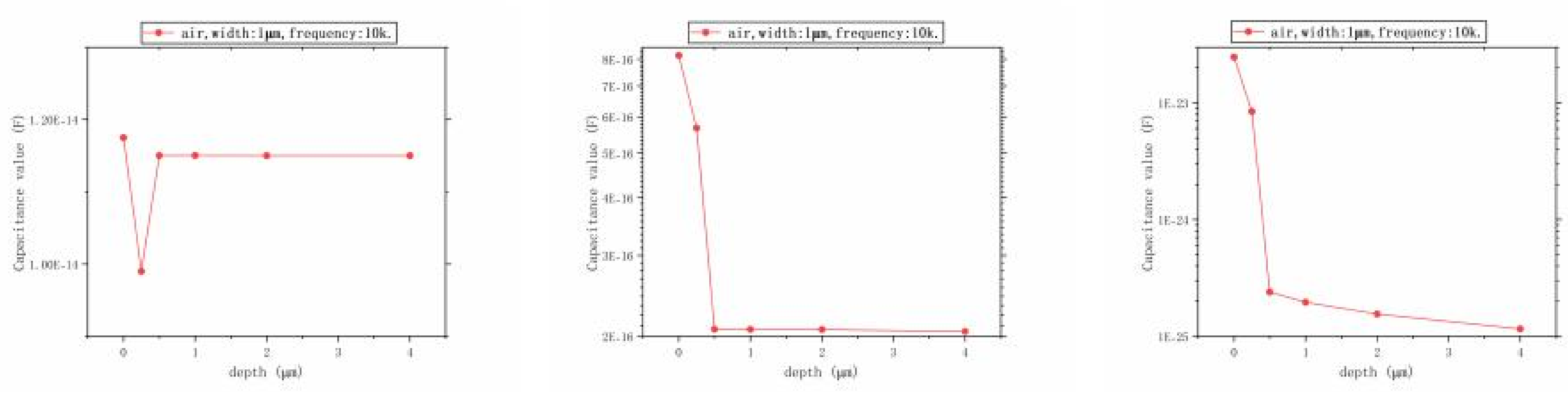
TCAD Simulation of Different Isolation Structure Parameters



(a)Coupling capacitance (b)Coupling capacitance (c)Coupling capacitance

Fig. 2 Effect of different isolation widths on capacitance parameters at a fixed depth of 4 μm.

- Setup: Fixed isolation depth (4 μm), tested isolation widths (0–10 μm) to study capacitance changes.
- Key Trends:
  - $C_{\text{inter-pad}}$: Drops by >3 orders of magnitude (width 1→10 μm), Fig. 2(b).
  - C_{bulk}: with theoretical calculations yielding ~3×10−16 F that matches Figure 3(b) experimental data. ($\varepsilon = 3\times10^{-11}$ F/m, $S = 5\times10^{-11}$ m², $d = 50$ μm)
- Minor Impact: Isolation width has little effect on C_{coupling}.



(a)Coupling capacitance (b)Coupling capacitance (c)Coupling capacitance

Fig. 3 Isolation Depth vs. Capacitance (Air, 1 μm Width, 10 kHz)

- Setup: Fixed isolation width(1 μm), tested isolation depths(0–4 μm) to study capacitance changes.
- Observe:
  The capacitance reduction at a depth of 0.25 μm is far less effective than that at other depths.