

Electrokinetic Self-Cleaning of Mixed-Phase Contaminants on Optical Sensors in Physical AI

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Summary: This paper presents an active electrokinetic cleaning device that integrates dielectrophoresis (DEP) and electrowetting-on-dielectric (EWOD) to simultaneously remove solid and liquid contaminants from optical sensors in Physical AI systems. By applying alternating current voltage to a transparent electrode, both particles and droplets are removed without mechanical moving parts. The restoration of object recognition accuracy in a contaminated optical sensor verifies the applicability of this approach.

Keywords: Physical AI, Electrokinetic cleaning, Dielectrophoresis, Electrowetting-on-dielectric, MEMS

Background

Artificial intelligence is integrated into various mechanical systems (e.g., automobiles, cameras, and robots) through on-device processing. This evolution toward Physical AI enables systems to autonomously perceive surroundings, make decisions, and execute physical actions. However, when these sensors are exposed to outdoor environments, solid particles (e.g., dust) and liquid droplets (e.g., raindrops) coexist and adhere to the surface. The resulting optical scattering causes degradation in object recognition accuracy and system reliability [1][2].

To address this challenge, active electrokinetic cleaning technology has garnered attention due to its lack of mechanical moving parts and rapid response [3]. The physical driving forces exerted on surface contaminants depend on the configuration of the non-uniform electric field and the underlying electrokinetic principles [4][5]. These factors dictate the cleaning efficiency of multi-phase contaminants exhibiting diverse physico-chemical properties. Consequently, it is essential to design a device architecture based on a dual-mechanism approach capable of simultaneously removing solid and liquid contaminants in operating environments.

This study proposes a self-cleaning device that integrates DEP and EWOD principles into a single transparent structure. We experimentally analyze the dynamic behavior of mixed-phase contaminants under AC voltage to quantitatively evaluate the surface cleaning efficiency.

Materials and methods

Electrokinetic removal utilizes non-uniform electric fields generated by applying AC voltage to multi-channel electrodes. Under this field, liquid droplets are driven by EWOD, which alters their contact angles and deforms the fluid interface, whereas solid particles are polarized and transported by DEP. To optimize the electrode geometry, a structural-electric field analysis was conducted using COMSOL Multiphysics. Based on these simulations, interdigitated electrodes were fabricated on a transparent glass substrate via semiconductor microfabrication processes (Fig. 1). Specifically, a 40 nm-thick indium tin oxide (ITO) layer was patterned as the electrode. Subsequently, a 2 μm -thick Parylene-C layer was deposited for electrical insulation, followed by a hydrophobic layer to control surface wettability, completing the multifunctional device.

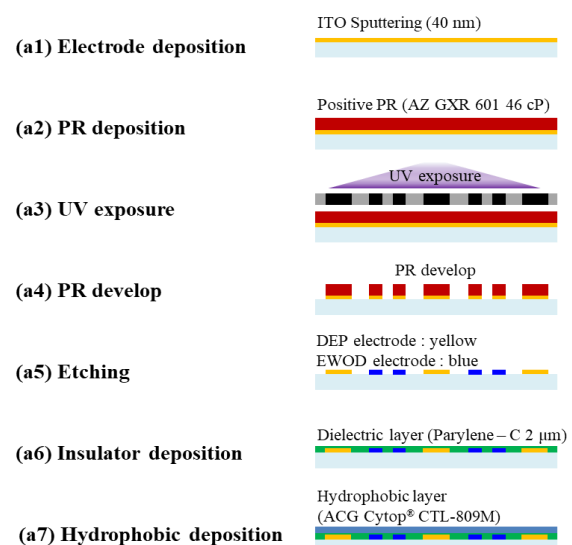


Fig. 1. Schematic images of microfabrication process.

Results

To evaluate the cleaning efficiency, the electrokinetic behavior of the contaminants was analyzed under a controlled environment (25 °C, 40 % RH). Initial removal experiments were conducted independently for each contaminant phase using the optimized interdigitated electrode pattern. Solid particles (50 μm diameter; glass beads, polymer beads, and iron powder) and liquid droplets of varying sizes were separately distributed on the device surface. AC voltage with varying frequencies was applied using a function generator coupled with a voltage amplifier. The dynamic response of the contaminants under the non-uniform electric field was recorded using a high-speed camera. Observations confirmed that liquid droplets were removed via EWOD-induced interface deformation, whereas solid particles were transported toward the electric field gradient via DEP (Fig. 2).

The surface states before and after the cleaning process were documented using an optical microscope. Residual contamination areas were quantitatively measured using ImageJ software. By analyzing the removal efficiency as a function of the applied voltage and frequency for each material, the optimal driving parameters were established. Subsequently, a mixed-phase contamination environment was simulated by co-depositing solid particles and liquid droplets on the surface. The simultaneous separation and removal of both phases were verified under the optimized parameters.

Finally, the proposed device was integrated into a surveillance camera module to validate its applicability. Artificial mixed-phase contamination applied to the optical sensor caused optical distortion, leading to object recognition failure. Upon activating the cleaning device, the contaminants were removed, and the recognition rate of the YOLOv26 object recognition model was restored to its pre-contamination baseline (Fig. 3).

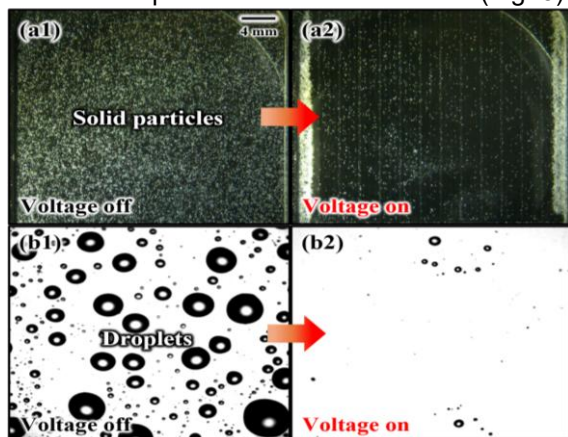


Fig. 2. Experimental results of contaminants removal using the active electrokinetic cleaning device: (a) solid particles; (b) Droplets



Fig. 3. Sequential snapshots of the electrokinetic removal of contaminants on an optical sensor and the restoration of object recognition: (a) Solid particles; (b) Droplets.

Conclusion

This study presents an active electrokinetic cleaning device that combines DEP and EWOD mechanisms for the simultaneous removal of mixed-phase contaminants. By restoring the object recognition accuracy of an obscured optical sensor, this technology demonstrates its potential as an active self-cleaning optical module to ensure the reliability of Physical AI systems, including autonomous driving and intelligent robotics.

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