Lead-free Bio-Inkjet Printing with Bulk KNN Actuators

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***Abstract*—This paper proposes a biocompatible inkjet printing architecture based on lead-free piezoelectric materials, specifically bulk KNN (K,Na)NbO_3, combined with chip-on-film (COF) driver IC implementation and silicon cavity integration. While Pb-free piezoelectrics have failed to replace PZT in industrial printing due to strict requirements on performance, endurance, and cost, bioprinting applications impose more moderate demands. Typical needs include droplet volumes of 1–10 pL, device lifetimes on the order of 10^6 shots, and operation within ± 50 V, all of which can be met by KNN-based actuators. We present the process flow, expected performance, and potential applications in bio-3D printing, cell patterning, and protein microarrays.**

I. Introduction

Inkjet printing has become a versatile technology in both industrial and consumer applications, with piezoelectric lead zirconate titanate (PZT) actuators serving as the dominant driver mechanism. Despite extensive research on lead-free piezoelectrics such as (K,Na)NbO_3 (KNN) and $Bi_{0.5}Na_{0.5}TiO_3$ (BNT), these alternatives have not replaced PZT in mainstream printing due to insufficient compatibility in key metrics such as piezoelectric coefficient d_{33}, long-term durability, and cost-effective manufacturing.

In biomedical applications, however, the design requirements differ fundamentally. Rather than extreme durability and maximum actuation strength, biocompatibility, chemical safety, and moderate performance are the primary needs. Typical bio-printing tasks—including cell patterning, protein array generation, and hydrogel dispensing—require droplet volumes in the range of 1–10 pL and endurance on the order of 10^6 shots, which are significantly less demanding than industrial printing standards.

This work therefore explores a Bio-Inkjet (Bio-IJ) architecture based on bulk KNN actuators, combined with chip-on-film (COF) driver integration and silicon cavity bonding. By tailoring the system to biomedical rather than industrial requirements, the proposed approach provides a feasible lead-free alternative that aligns with environmental regulations and biological safety.

II. Background: Pb-free Piezoelectrics

Research on lead-free piezoelectrics has been pursued for more than two decades as part of global efforts to replace lead zirconate titanate (PZT) with environmentally benign alternatives. Among the most prominent candidates are (K,Na)NbO_3 (KNN), $Bi_{0.5}Na_{0.5}TiO_3$ (BNT), and Sc-doped AlN (ScAlN).

KNN typically exhibits a piezoelectric coefficient d_{33} in the range of 150–250 pm/V, with optimized compositions reaching up to 300–400 pm/V, and a Curie temperature exceeding 400 °C. These properties make it suitable for moderate-displacement actuators. In contrast, ScAlN provides a more modest d_{33} of 20–30 pm/V, but its excellent CMOS compatibility and feasibility for thin-film MEMS integration have positioned it as an attractive material for micro-scale devices. BNT and related systems have also been investigated, though issues such as depolarization and processing complexity have limited their adoption.

Despite these advances, industrial printing applications have not embraced Pb-free piezoelectrics. The primary obstacle has been the expectation of *full PZT compatibility*—requiring identical performance in terms of strain output, durability over 10^9 cycles, and manufacturing cost. Such stringent requirements exceed the current capabilities of KNN, BNT, or ScAlN.

In biomedical printing, however, these limitations are less critical. Because the performance demands are moderate and biocompatibility is a non-negotiable requirement, Pb-free piezoelectrics can be reconsidered as practical actuator materials for Bio-Inkjet systems.

III. Proposed Architecture

The proposed Bio-Inkjet (Bio-IJ) actuator system is designed to balance biocompatibility, manufacturability, and sufficient actuation performance for biomedical applications. Its main components are as follows:

- **Bulk KNN multilayer stack actuator**: A 200–500 μm thick piezoelectric stack providing moderate displacement suitable for picoliter-scale droplet ejection.
- **COF driver IC**: A chip-on-film high-voltage driver with 16–32 channels, operating at up to ± 50 V, and incorporating waveform RAM with SPI control for flexible pulse shaping.
- **Si cavity and nozzle array**: A silicon-etched cavity directly bonded to the actuator, with nozzles of $\varphi 8\,\mu\mathrm{m}$ diameter producing droplets in the 3–5 pL range.
- **Reservoir and back pressure control**: A fluidic supply stabilized at approximately -2.0 kPa using a PID-

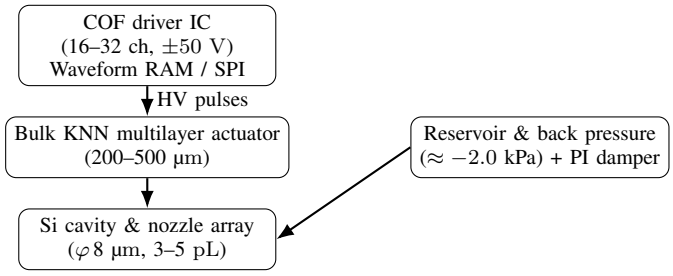

Fig. 1. System architecture of the proposed Bio-Inkjet (Bio-IJ). A bulk KNN actuator, COF high-voltage driver, silicon cavity/nozzles, and fluidics (back-pressure with PI damper) are integrated.

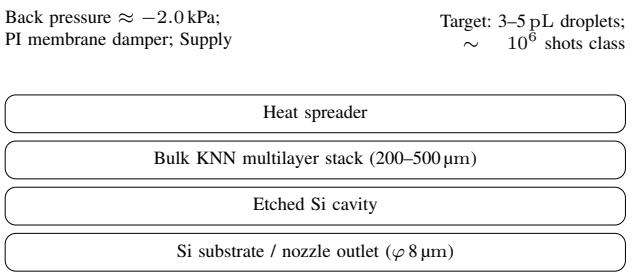

Fig. 2. Cross-sectional schematic of the Bio-IJ printhead. The KNN stack is bonded to a silicon cavity with $\varphi\,8\,\mu\mathrm{m}$ nozzles; fluidics provide back-pressure stabilization and damping.

controlled regulator to ensure consistent meniscus positioning.

- **PI membrane damper**: A polyimide-based damping layer integrated in the reservoir to suppress pressure fluctuations and prevent satellite droplets.

The associated *process flow* begins with fabrication of the bulk KNN stack and electrode finishing, followed by terminal cutting and COF assembly. The actuator is then mounted with a heat spreader for thermal management and finally bonded to the silicon cavity structure, resulting in an integrated Bio-IJ printhead module.

IV. Applications

The proposed Bio-Inkjet architecture enables several key biomedical applications in which moderate actuation performance, precise droplet control, and biocompatibility are prioritized over extreme durability:

- **Cell patterning**: Controlled deposition of living cells into predefined patterns for tissue engineering and regenerative medicine. Gentle actuation and droplet volumes of 1–10 pL support high cell viability, with survival rates above 80% reported under comparable shear stress conditions.
- **Protein and DNA microarrays**: Picoliter-scale dispensing of biomolecules onto functionalized substrates for high-throughput screening, diagnostics, and drug discovery. The ability to generate uniform, sub-100 µm spots is critical for assay reproducibility.
- **Hydrogel 3D printing**: Layer-by-layer deposition of biocompatible hydrogels, followed by UV or thermal curing, to fabricate soft scaffolds for cell culture and organ-on-chip platforms. Precise droplet placement ensures structural fidelity and material homogeneity.

These use cases demonstrate that the moderate performance of bulk KNN actuators—picoliter droplet generation at voltages below ± 50 V—is sufficient to meet biomedical requirements. Here, droplet volume control, biocompatibility, and integration with fluidic handling systems are far more critical than the billion-cycle endurance demanded in industrial printing.

V. Conclusion

This paper has proposed a Bio-Inkjet (Bio-IJ) architecture based on bulk KNN actuators as a lead-free alternative to conventional PZT-based printheads. By combining multilayer KNN stacks, COF driver ICs, and silicon cavity integration, the system achieves picoliter-scale droplet generation under moderate voltages while ensuring material biocompatibility.

Unlike industrial printing, where full PZT compatibility in terms of maximum d_{33}, billion-cycle endurance, and cost efficiency is required, biomedical printing places emphasis on safety, controlled droplet volume, and operational reliability over shorter lifetimes. The proposed approach aligns well with these requirements, providing sufficient performance for applications such as cell patterning, protein microarrays, and hydrogel 3D fabrication.

These findings highlight bulk KNN as a practical foundation for standardizing lead-free Bio-IJ systems in research, clinical, and educational domains. Future work will involve experimental validation of droplet formation, long-term reliability testing under bio-relevant conditions, and system integration with existing bioprinting workflows.

References

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