Electrically Programmable Microvalve for On-Demand Drug Delivery

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Primary CNF Tools Used: Oxford 81/82 etcher, Oxford 100 ICP etcher, Oxford Cobra ICP; Xactix Xenon Difluoride, YES EcoClean Asher, Gamma Automatic Coat-Develop Tool, SC 4500 odd-hour evaporator, OEM M1 AlN Sputter, AJA Sputter Tool, Heidelberg DWL2000, ABM Mask Aligner, Oxford FlexAL, Oxford PECVD, Plasma-Therm Takachi HDP-CVD, DISCO Dicing Saw, Zeiss SEM, KLA P7 Profilometer, Keyence VHX-7100 Digital Microscope

Abstract:

We present a microactuator-integrated nanofluidic membrane system that enables actively programmable and reversible control of molecular transport for advanced drug delivery applications. This platform combines two key technologies: (1) electrostatically gated nanofluidic channels for charge-selective diffusion and (2) Pd/Ti bilayer microactuators for mechanically regulating bulk flow. The actuators, operating under low-voltage input (−1.2 V to +0.6 V), undergo reversible bending via hydrogen absorption without gas evolution, providing robust and fatigue- resistant control over valve states. Integrated with a hexagonal array of slit nanochannels, the system supports dynamic, spatially patterned gating of molecular transport. Unlike conventional controlled-release systems that rely on passive diffusion or fixed release profiles, our approach offers real-time, reconfigurable, and multiplexed control over drug dosing. Preliminary experiments demonstrate highly uniform actuator response, long-term durability over hundreds of cycles, and programmable region-specific valve activation. This technology provides a versatile foundation for implantable drug delivery systems with closed-loop feedback capability, and may be extended to broader microfluidic and bio-interfacing applications.

Summary of Research:

Precise, responsive drug delivery remains a central challenge in biomedical engineering, especially for chronic diseases requiring variable dosing over time [1, 2]. Conventional systems—such as polymer matrices, osmotic pumps, or diffusion-based capsules—typically offer fixed or pre- programmed release profiles, lacking adaptability to dynamic physiological conditions.

Nanofluidic membranes offer electrostatic selectivity, but their functionality is limited to specific molecular charges [3]. To overcome these constraints, we propose a hybrid strategy that combines nanofluidic

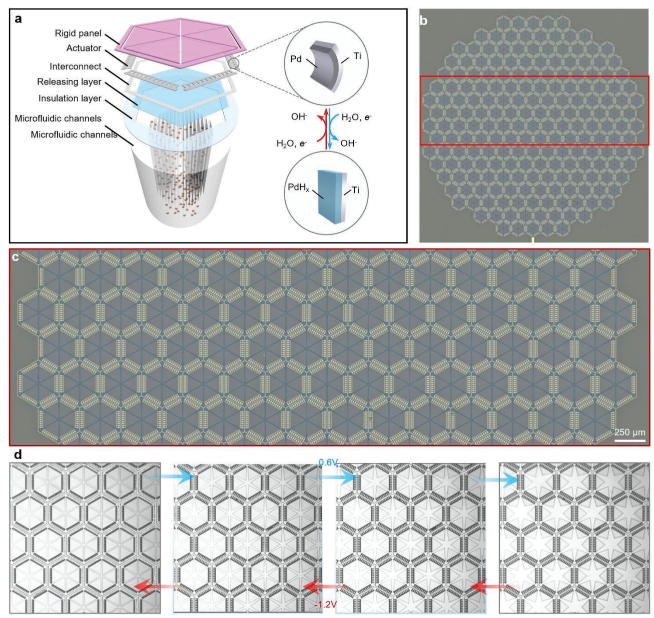

Figure 1: Integrated microactuator-nanofluidic membrane platform for voltage-controlled drug delivery. (a) Schematic diagram of the device architecture. A Pd/Ti bilayer microactuator is integrated on top of a nanofluidic membrane consisting of layered microfluidic channels, insulation, and releasing layers. When voltage is applied, the actuator bends due to hydrogen absorption in Pd, forming PdHx, enabling reversible switching between open and closed states without bubble formation. (b) Optical micrograph of a fabricated circular array containing hundreds of individual actuator units arranged in a hexagonal lattice. The red box outlines the region shown in (c). (c) Zoom-in view of the actuator array, showing the detailed tiling pattern of hexagonal units, each with a central membrane and six radial flaps. The actuators are fabricated with high uniformity across the array. Scale bar: 250 µm. (d) Sequential optical images showing voltage-controlled actuation: valves remain closed at 0 V, open at +0.6 V, and return to the closed state at −1.2 V. The actuation is robust and repeatable for over 300 cycles using 100 nm Pd / 100 nm Ti bilayer actuators.

selectivity with actively reconfigurable microvalves for spatiotemporal control of molecular transport.

We have developed an electrically programmable microvalve array integrated with a nanofluidic membrane to enable real-time, spatially controlled drug delivery. The device combines Pd/Ti bilayer electrochemical actuators with dense arrays of nanoslits for charge-selective transport, enabling dual-mode regulation of molecular flow through both electrostatic and mechanical mechanisms.

Figure 1a illustrates the device architecture, where thin-film actuators are monolithically integrated atop nanofluidic membranes consisting of Si-based slit channels, insulation, and fluidic layers. Upon application of a voltage (−1.2 V to +0.6 V), the Pd layer undergoes hydrogen absorption, forming PdHx, which induces out-of-plane bending relative to Ti due to lattice expansion. This mechanical deformation allows each valve to reversibly switch between open and closed states (Figure 1d). The actuation process is stable, bubble-free, and repeatable across more than 300 cycles with minimal fatigue. The fabricated actuator array, arranged in a hexagonal tiling (Figure 1b–c), demonstrates high patterning fidelity and uniform performance. Each unit consists of six independent actuator flaps surrounding a central nanochannel inlet. Actuation behavior is highly robust, with >95% of flaps responding uniformly under each voltage sweep. Each device utilizes 100 nm Pd / 100 nm Ti bilayers.

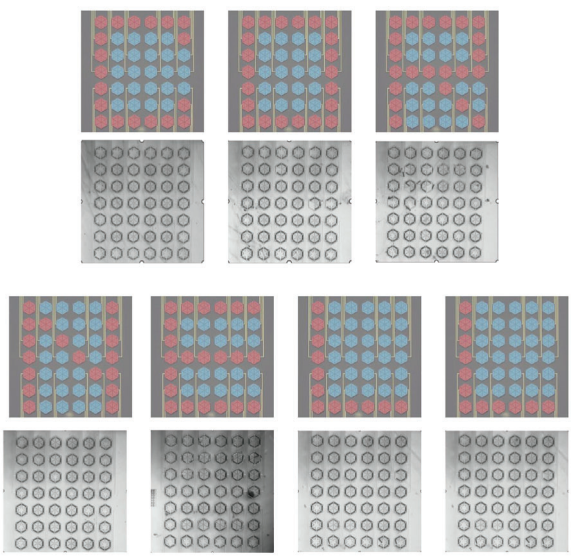

Figure 2: Spatially programmable microvalve actuation for pattern-defined molecular gating. Top two rows: Predefined activation patterns and corresponding optical micrographs demonstrating selective spatial control of microactuator arrays. Colored overlays (red and blue) represent distinct voltage-addressable regions activated under orthogonal driving signals. Each pattern corresponds to a unique flap-opening configuration across the array, allowing for reconfigurable and localized drug release profiles. Bottom two rows: Additional examples of spatially programmed actuation with varied addressable regions. Designed activation maps (top) are followed by corresponding actuation results (bottom), confirming high spatial fidelity and reproducibility across repeated cycles. The platform enables complex programmable gating geometries for multiplexed delivery zones or patterned molecular access.

To demonstrate spatial programmability, we designed multi-region addressable patterns using independently biased electrode zones (Figure 2). Simulated activation masks (colored blue and red) match closely with experimental actuation results across multiple configurations, confirming our ability to locally modulate flow through desired patterns. This programmable gating enables localized drug dosing, zonal delivery control, and dynamic therapeutic scheduling within a single device.

The hybrid system addresses limitations of current controlled-release platforms, which often rely on static polymer matrices, osmotic gradients, or diffusion-based mechanisms that lack real-time control [2,4]. In contrast, our platform enables both charge-selective gating through electrostatic interaction within the nanochannels and physical flow modulation via microactuation. This allows for transport of a wide range of molecules, including neutrals and cations, not previously accessible via electrostatic gating alone.

Conclusions and Future Work:

Future efforts will focus on packaging and biocompatibility, in vivo validation, and integration with real-time feedback systems for autonomous control. Ultimately, this microvalve-nanofluidic hybrid architecture could serve as the foundation for adaptive therapeutic implants, multi-analyte chemical release platforms, or sensor-responsive systems in closed-loop medical devices.

References:

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