Electrically Programmable Microvalve for On-Demand Drug Delivery

CNF Project Number: 241616
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Primary Source(s) of Research Funding: National Science Foundation

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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

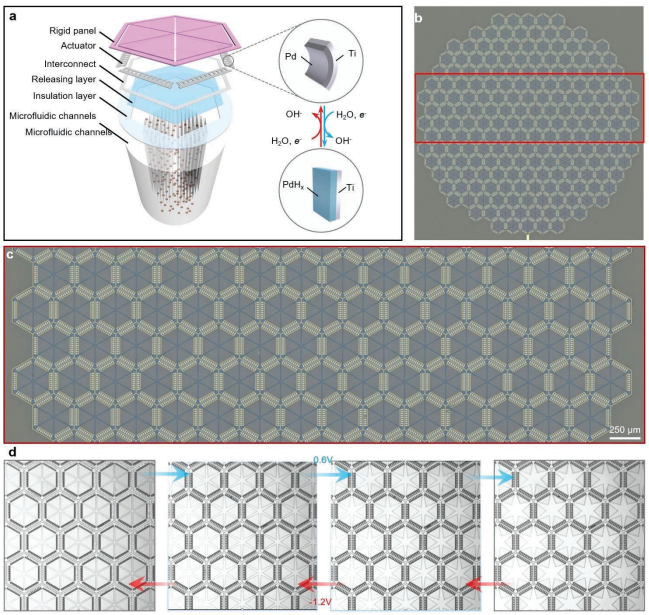

Figure 1: Integrated microactuator-nanofluidic membrane platform for voltage-controlled drug delivery. (a) Schematic diagram of the device architecture. A Pd/Ti bilayer microactuator is integrated on top of a nanofluidic membrane consisting of layered microfluidic channels, insulation, and releasing 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.

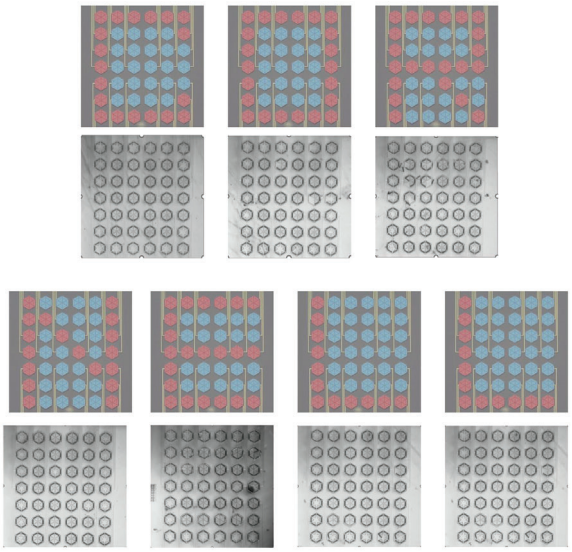

Figure 2: Spatially programmable microvalve actuation for pattern-defined molecular gating. Top two rows: Predefined activation patterns and corresponding optical micrographs demonstrating selective spatial control of microactuator arrays. Colored overlays (red and blue) represent distinct voltage-addressable 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.

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Programmable Magnetoelastic Energy Landscapes for Autonomous Microscopic Machines

CNF Project Number: 296421
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Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV stepper, Gamma Automatic Coat-Develop Tool, JEOL 9500 EBL, SC 4500 odd-hour evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 ICP etcher (left side), Unaxis 770 Deep Silicon Etcher, Oxford FlexAL, Plasma-Therm Takachi HDP-CVD, Zeiss SEM, Veeco AFM.

Abstract:

The function of many microscopic machines is determined not only by their structure, but by conformational, dynamic changes in the shape of a device or molecule. Developing design paradigms for these microscopic machines requires the development of novel experimental platforms with controlled energy landscapes, and the ability to drive transitions between energy minima. Here, we introduce such a platform based on panels covered with programmable nanomagnetic domains, connected by flexible elastic hinges. We show that the combination of magnetic and elastic parameters gives rise to tunable energy minima, which can be accessed by applying an external magnetic field. Structuring the elastic or magnetic degrees of freedom of the device leads to the creation of multiple stable states, and as a first step we demonstrate a basic paradigm for three-state work cycles. We combine these principles to produce conformation-dependent locomotion via a magnetic walker with bistable energy landscape.

Research Summary:

The function of many biological and synthetic micromachines is realized by targeted conformational changes (1). Such functions include catalysis, sensing, force and torque generation creating concentration gradients, fluid pumping, light steering, and locomotion. However, the rational design of microscopic machines that undergo conformational change and transduce energy into mechanical work remains an outstanding goal. A key obstacle is the difficulty of modeling and designing the entire energy landscape of systems driven by electrostatic and chemical interactions, and furthermore to perform mechanical work by controllably actuating transitions between local energy minima (2).

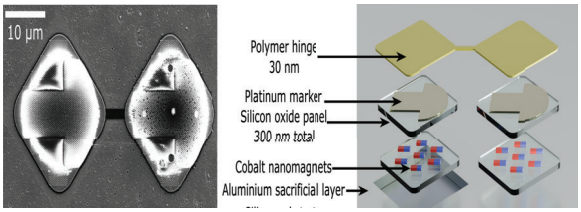

Figure 1: Scanning electron microscope image of the device, with schematic showing the device layer structure.

Here, we present a new experimental platform for programmable energy landscapes based on microscale magneto- elastic structures (Figure 1) (3,4,5). Competing elastic and magnetic interactions allow for the design and construction of energy landscapes with many potential minima, whose depth is controlled by device parameters. At the same time, transitions between these constructed energy minima can be actuated by applying directed torques in the form of external magnetic fields.

Combining magnetic and elastic design degrees-of-freedom allows for the construction of a two-state bistable shutter. Such a bistable shutter toggles between two states, here an “open" and a “closed" state, which can differentially control light transmission at the location of the free panel. In order to actuate transitions between local energy minima, we use an external magnetic field to apply a torque to the free panel. Once the panels are close enough, magnetic interactions between the panels stabilize the “closed state”. To re-access the “open” state, we apply an increasing magnetic field, so that the stable state of the system switches to being aligned with the external magnetic field (Figure 2). This two-panel, one elastic degree-of- freedom device thus provides a minimal example of a bistable energy landscape with controlled minima depth, with a single actuated transition between the two stable states.

In addition to controlling an on/off state, many

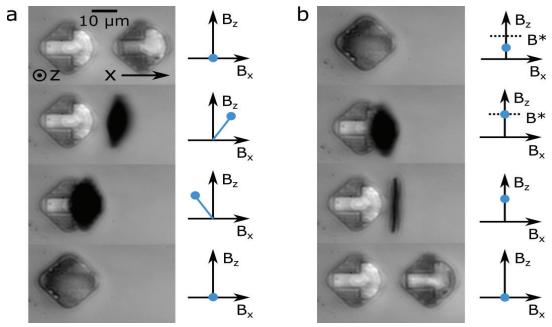

Figure 2: Using external magnetic fields to actuate a bistable shutter. (a) Sequence of images and accompany magnetic field magnitudes for closing a magnetic shutter. Magnetic interactions stabilize the closed position when the magnetic field is turned off. (b) Sequence of images showing the shutter re-opening upon the application of a finite magnetic field.

microscopic machines perform some work on the environment, such as pumping fluid, which requires a nonreciprocal cycle through configuration space. We construct such a nonreciprocal cycle by twisting the flexible elastic hinge to access a third stable state in the energy landscape (Figure 3). Each cycle of the machine pumps fluid in a rotational motion. This pumping is enabled by the difference in cross-sectional drag between the first and second steps of the work cycle, where the energy stored in the system by bending the hinge in-plane is released out-of-plane and transferred into rotational fluid flow.

The work generated (in the form of fluid flow) by this three-state device is realized by navigating between minima in an energy landscape. Such navigation requires a relatively complex control sequence in order to guide the free panel through the correct sequence of motions. In contrast, molecular motors convert a scalar energy input (ATP) to translate along a symmetry-broken direction. Similarly, we utilize a unidirectional magnetic field as our scalar energy input, and break the symmetry of the locomotion direction by bistability in the energy landscape of the magnetic device. In this case, devices operate within an energy landscape with multiple basins, where the initial condition of a device determines the basin about which it operates. The unidirectional magnetic field then serves as an energy source to drive work cycles within each basin, which translate to motion in opposite directions (Figure 4).

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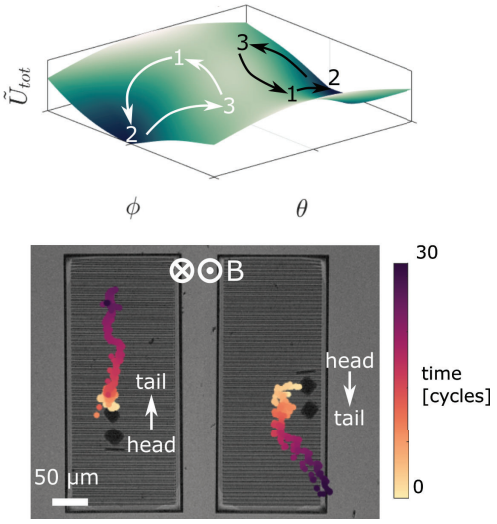

Figure 4: (a) Energy landscape with two minima, allowing for two independent work cycles, (b) Center-of-mass motion of two magnetic walkers with tails facing opposite directions, under the same magnetic actuation, with the time indicated by the shared color scale on the right.

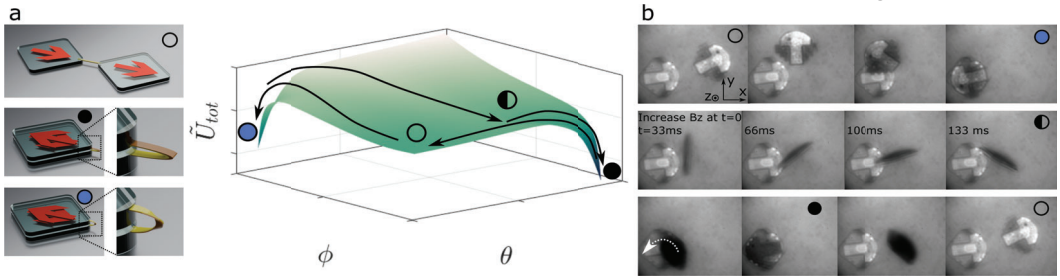

Figure 3: Creating a microfluidic rotary pump by navigating a multi-stable energy landscape. Diagram of the stable states of the system, together with the predicted energy landscape. (b) Series of optical microscope images showing a three-state work cycle, marked by symbols corresponding to the illustrations in (a).

Bioinspired Acoustic Particle Velocity Sensor

CNF Project Number: 322424

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Primary CNF Tools Used: LPCVD silicon nitride deposition

Abstract:

Inspired by the velocity-sensitive ears of small animals [1, 2], vector acoustic sensing using viscous-driven mechanical structures is emerging as a promising alternative to traditional pressure-based sound detection. We have performed silicon nitride deposition using CNF, which serves as the structural layer for forming slender microbeams used in bioinspired acoustic particle velocity sensing. This vector sensing approach overcomes fundamental limitations of scalar pressure-based acoustic sensors, offering intrinsic advantages in directional sound detection, source localization, and noise rejection.

Research Summary:

We used CNF facilities for silicon nitride deposition on double-side- polished wafers. The deposited silicon nitride served as the structural layer for fabricating slender microbeams designed for bioinspired acoustic particle velocity sensing.

Conclusions and Future Steps:

We successfully fabricated slender silicon nitride microbeams (Figure 1) based on the deposition work performed at CNF, which are currently being characterized for their performance in acoustic particle velocity sensing. As a next step, we plan to use the Nanoscribe 3D printer at CNF to fabricate 3D microstructures on the silicon nitride beams. These structures aim to enhance acoustic performance by mimicking the 3D geometry of mosquito antennae, which are capable of detecting extremely weak sounds.

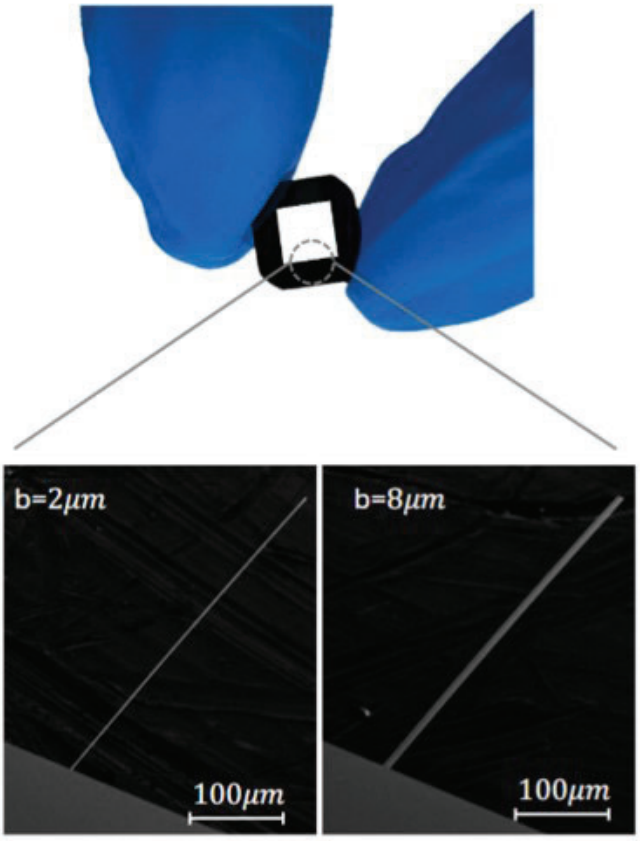

Figure 1: False-color scanning electron microscope image of a diffractive robot, consisting of (yellow) ALD silicon oxide hinges, (red) programmable cobalt nanomagnets, and (blue) rigid silicon oxide panels.

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