MEMS, Field-Emitter, Thermal, Fluidic Devices, and Robotics

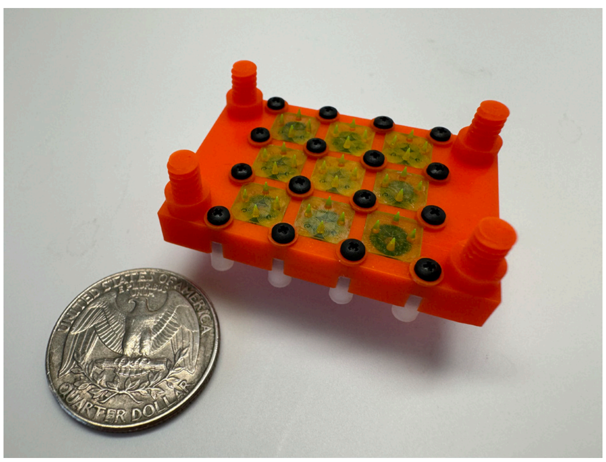
Modular, 3D-printed Electrospray Thrusters for High-impulse Maneuvers in CubeSats

H. Kim, L. F. Velásquez-García
Sponsorship: MathWorks Fellowship, the MIT Portugal Program

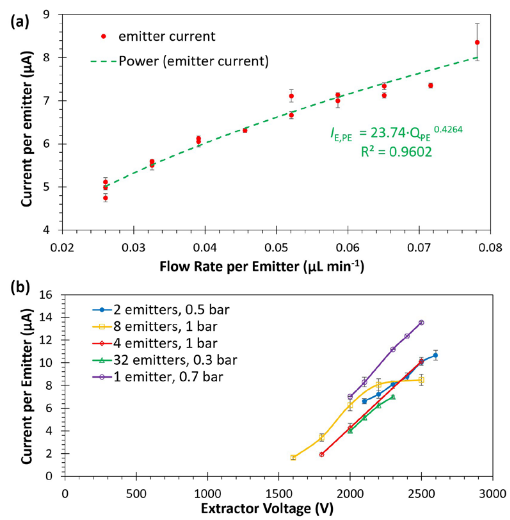
Electrospray thrusters are a type of electric propulsion system that offers high specific impulse, making them ideal for maneuvering small satellites. Traditionally, the fabrication of electrospray thrusters has been conducted in semiconductor cleanrooms to achieve precise micro-scaled features. However, this process is expensive, time-consuming, and incompatible with in-space manufacturing. This study presents a proof-of-concept demonstration of a novel, droplet-emitting electrospray thruster array design for CubeSats that is fully additively manufactured.

The electrospray thruster design developed in this study integrates two vat photopolymerization three-dimensional (3D) printing technologies, i.e., digital light processing (DLP) for the meso-scaled features, and two-photo polymerization (2PP) for the micro-scaled features. Each 2PP-printed module contains 4 emitters with optimized, 50-µm-diameter microfluidic channels to ensure uniform operation across the emitter arrays. These modules are connected in parallel using a DLP-printed manifold block to increase the thruster's throughput (Figure 1).

Testing of devices with up to 8 modules (32 emitters in total) in vacuum demonstrated stable and uniform operation for the first time as a 3D-printed, droplet-emitting electrospray emitter array with near 100% beam transmission (Figure 2). Both pressure and voltage were evaluated as ways to control the emitted current and thrust, with voltage control proving to be a more effective and simpler approach, despite being less explored in the literature for electrospray in the droplet emission regime. The estimated thrust and specific impulse are comparable to, or better than, those reported for other droplet-emitting electrospray thrusters. These results suggest that the proposed manufacturing approach is a promising method for developing efficient electrospray thrusters for space propulsion.



▲Figure 1: Optical image of a device with 9 modules, without the extractor electrode, next to a US quarter. From first Reading.



▲Figure 2: (a) Per-emitter current versus flow rate for a device biased at 2000 V, and (b) per-emitter current versus extractor voltage for a device tested with different pressures. Emitter electrode was grounded; error bars represent one standard deviation.

FURTHER READING

- H. Kim and L. F. Velásquez-García, "High-impulse, Modular, 3D-printed CubeSat Electrospray Thrusters Throttleable via Pressure and Voltage Control," *Advanced Science*, p. 2413706, 2025. DOI: 10.1002/advs.202413706
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Advanced Cooling of Electronics via Additive Manufacturing and AI

H. Kim, L. F. Velásquez-García
Sponsorship: MathWorks Fellowship

The increasing demand for compact and efficient power electronics highlights the need for advanced thermal management solutions. Traditional liquid-cooled heat sinks, typically fabricated via subtractive or formative manufacturing, are limited in their ability to address nonuni-form heat loads due to their simple geometries. This research aims to develop a low-cost, high-performance, liquid-cooled heat sink for electronics by integrating generative artificial in-telligence (AI)-driven design with three-dimensional (3D) printing using highly thermally conductive composite resins. Leveraging additive manufacturing can realize complex, freeform internal cavities tailored to specific thermal profiles to significantly enhance heat dissipation. The devices will be made via vat photopolymerization using ceramic-loaded polymer resin as feedstock. The ceramic filler increases the thermal conductivity of the composite.

Current work focuses on developing a genetic algorithm to generate printable, 2D liquid channel designs that maximize heat transfer performance. The algorithm includes initialization, evaluation, mutation, and crossover stages, iteratively refining designs based on simulated temperature distributions. To address manufacturability constraints inherent to the chosen 3D printing method, the initialization phase generates non-intersecting centerline paths on a discretized grid, ensuring that resulting channel geometries are printable (Figure 1). The evaluation phase, which integrates automated 3D model generation and thermal simulation, assesses the effectiveness of each design. The algorithm then iteratively seeks the best-performing designs by mutating and merging features from the previous iterations.

Future research will explore transitioning from genetic algorithms to other generative AI techniques and extend the design framework to full 3D heat exchanger architectures. This integrated approach aims to unlock the full potential of additive manufacturing for custom, high-performance thermal management solutions.

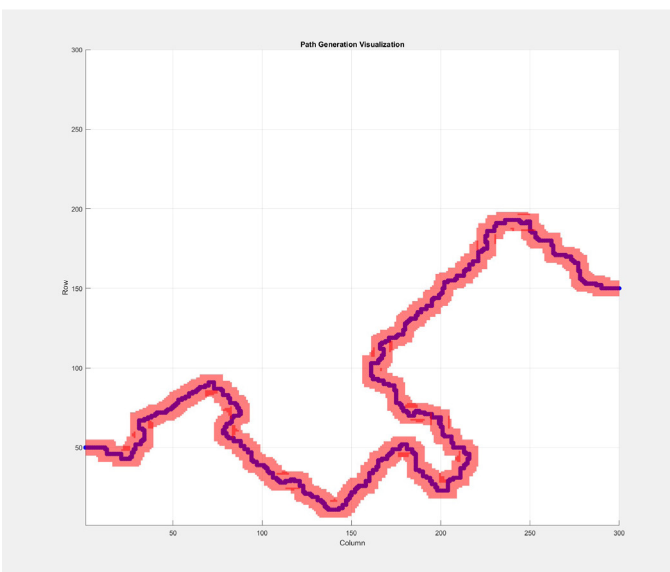

Figure 1: A random, constant-width path generated between designated start and end points for the initialization phase of the genetic algorithm, with printability constraints taken into account.

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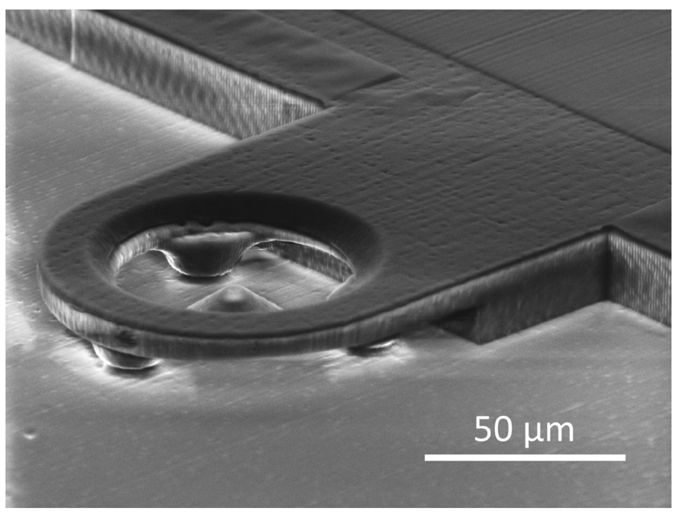
- T. Wu, B. Ozpineci, and C. Ayers, "Genetic Algorithm Design of a 3D Printed Heat Sink," *2016 IEEE Applied Power electronics Conference and Exposition (APEC)*, pp. 3529-3536, 2016. DOI: 10.1109/APEC.2016.7468376
- Y. Manaserh, A. R. Gharaibeh, M, I. Tradat, S. Rangarajan, B. G. Sammakia, and H. A. Alis-sa, "Multi-objective Optimization of 3D Printed Liquid Cooled Heat Sink with Guide Vanes for Targeting Hotspots in High Heat Flux Electronics," *International J. of Heat and Mass Transfer*, 184, p. 122287, 2022. DOI: 10.1016/j.ijheatmasstransfer.2021.122287
- H. Kim and L. F. Velásquez-García, "High-impulse, Modular, 3D-printed CubeSat Electrospray Thrusters Throttleable via Pressure and Voltage Control," *Advanced Science*, p. 2413706, 2025. DOI: 10.1002/advs.202413706

2-photon Photolithography Fabrication of “Pixel” Electrospray Thrusters

C. J. Nachtigal, S. Dhulipala, C. M. Portela, P. C. Lozano
Sponsorship: NASA Space Technology Graduate Research Office Grant (80NSSC23K1174), U.S. Air Force Office of Scientific Research (FA9550-19-1-0104)

Electrospray thrusters (ESTs) are a promising form of electric propulsion in small satellite and deep space applications due to their high specific impulse and low thrust. ESTs consist of an array of micro emission sites where propellant is fed to and propelled from via a voltage application to the emitter with respect to a downstream grounded extractor electrode. ESTs lack in the length of their lifetime, due to electrical shortages at a single emission site causing premature full array shortage. They also lack efficiency, due to improper extractor alignment and poor emitter manufacturing precision affecting emission site stability and purely ionic regime emission. To remedy this, we propose an EST design consisting of precise capillary emitters with an integrated extractor array consisting of single extractors connected via fuses to prevent shortage propagation and ensure extractor alignment. To realize this design, this work uses 2-photon photolithography to build the emitter capillaries and integrated extractor base and liftoff of sputter-coated nichrome to pattern the extractors and fuses. We examine the fabrication feasibility on porous glass substrates and on 50-100-µm-diameter etched through-holes in silicon wafers to allow for passive propellant uptake. We determined the contact angle and dielectric breakdown of the structure and designed a prototype to be compatible with voltages over 1200 V, which is well within the necessary firing voltage range that is simulated. Further, the design allows for an emitter pitch of less than 80 µm, which can be reduced further in future iterations, greatly densifying arrays and increasing the potential thrust per area of ESTs.



▲ Figure 1: Scanning electron microscope image of single 3-µm-diameter “pixel” emitter capillary fabricated in UpBrix with connected extractor contact pad and patterned Ag and Ti on Si over 100-µm-diameter propellant-feeding through hole.

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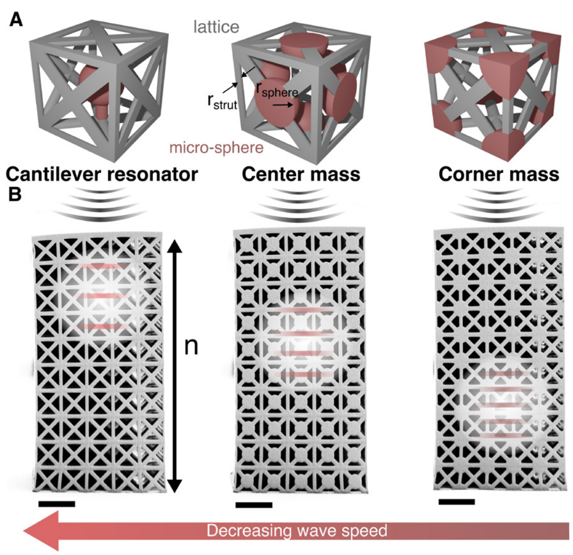
Tailored Ultrasound Propagation in Microscale Metamaterials via Inertia Design

R. Sun, J. Lem, Y. Kai, W. DeLima, C. M. Portela
Sponsorship: Kansas City National Security Campus, MIT Institute for Soldier Nanotechnolgies, MIT Mechanical Engineering MathWorks Seed Fund, NSF Graduate Research Fellowship Program

The quasi-static properties of micro-architected (meta) materials have been extensively studied, but their dynamic responses, especially in acoustic metamaterials with engineered wave propagation behavior, represent a new frontier. However, challenges in miniaturizing and characterizing acoustic metamaterials in high-frequency (megahertz, MHz) regimes have hindered progress toward experimentally implementing ultrasonic-wave control.

We present and validate a micro-inertia design framework for programming quasi-static and dynamic (MHz range) responses of three-dimensional micro-architected materials. Using a simple braced-cubic unit cell design, we present two micro-inertia placement strategies and explain how each tunes quasistatic stiffness and dynamic longitudinal-wave velocities differently in these metamaterials. We fabricate all designs in a single-step, single-material two-photon lithography process, which enables their microscale implementation. Through quasi-static nanomechanical compression experiments and finite-element analysis, we demonstrate that micro-inertia location changes stress distribution within the materials and lowers the effective stiffness increase per added unit of mass. This presents a deviation from the classical stiffness scaling laws for architected materials, which we describe as partially "decoupling" mass and stiffness properties. Using the laser-induced resonant spectroscopy method, we experimentally demonstrate that decoupling mass and stiffness enables tunable elastic-wave velocities in the MHz regime. Our framework provides a vast design library of elasto-dynamic properties via simple geometric changes, which we use to spatially and temporally program ultrasonic wave propagation in microscale materials and an acoustic demultiplexer.

Altogether, the capabilities of this micro-inertia design framework expand the achievable property space by partially decoupling mass and stiffness. This parametric design framework establishes independently tunable quasi-static and elasto-dynamic properties without requiring complex design algorithms, enabling straightforward design and fabrication of microscale acoustic metamaterials and devices.



▲ Figure 1: (A) Three braced-cubic sample designs increase relative density by increas-ing strut radius and nodal mass radii. (B) Various mass-addition schemes provide a route to achieve both tunable quasi-static stiffness and longitudinal wave velocities. Scale bars 20µm.

FURTHER READING

- Y. Kai, S. Dhulipala, R. Sun, J. Lem, W. DeLima, T. Pezeril, and C. M. Portela, "Dynamic Diagnosis of Metamaterials through Laser-induced Vibrational Signatures," *Nature*, vol. 623, no. 7987, p. 514-521, 2023.

3D-integrated Circuits in GaN/Si CMOS/Glass for High-frequency, High-data-rate Applications

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Sponsorship: SRC Joint University Microelectronics Program 2.0 (Grant no. 2023-JU-3136), National Defense and Science Graduate Fellowship

Gallium nitride (GaN) transistors are enabling the next generation of high-efficiency, high-power, and high-frequency integrated circuits. Furthermore, demonstrations of low-voltage GaN radio frequency (RF) switches for front-end modules (FEM) and low-noise figures in GaN low-noise amplifiers (LNAs), are broadening the applications of GaN into the mobile, artificial intelligence (AI), and quantum sectors. But this excellent performance comes with a high cost, due to limited wafer sizes and back-end-of-line (BEOL) metallization options. On the other hand, a Si complementary metal-oxide-semiconductor (CMOS) allows access to state-of-the-art 300-mm BEOL and digital circuit design.

Revolutionizing GaN chip design requires a holistic approach through integration with Si CMOS. This work, through these two approaches, makes three-dimensional (3D) GaN chips design more cost-effective while providing orders of magnitude improvement over convention 2D-circuits in Si or GaN-only front-end-of-line (FEOL). With the combination of Si CMOS digital, bias, and matching chips, high-frequency GaN dielets are integrated in a highly scaled manner through using direct Cu-Cu bonding for several 3D-amplifier first demonstrations. Such integration offers low RF losses as well as near-seamless-bonding interfaces. Similarly, glass offers a low-cost packaging option for multi-chiplet systems. Large substrate sizes and panel thickness down to 30 μm enable the next generation of packaging for nano-systems at scale, while also allowing for novel thermal cooling solutions such as microfluidic, two-phase vapor, etc. With the lamination of low-loss dielectric Ajinomoto build-up film (ABF) layers in glass, a highly capable package for 3D-RF stacking can be created. This work integrates GaN dielets directly in this glass package for the first time; it also studies and quantifies their properties.

GEVO: Memory-Efficient Monocular Visual Odometry Using Gaussians

D. Gao, P. Z. X. Li, V. Sze, S. Karaman
Sponsorship: Amazon, MathWorks Fellowship, NSF CPS

High-fidelity 3D scene reconstruction with a monocular camera supports applications on mobile devices like micro-robots and AR/VR headsets, where access to the off-chip memory dominates the compute energy. While Gaussian Splatting (GS) enables detailed reconstruction, existing GS-based SLAM systems are memory-inefficient because they store numerous past images to retrain Gaussians to prevent catastrophic forgetting, leading to excessive memory usage.

Thus, we present GEVO, a GS-based SLAM framework that achieves comparable fidelity as prior works by rendering (instead of storing) them from the existing map. Novel Gaussian initialization and optimization methods are proposed to delay the degradation of the rendered images over time. In various environments, GEVO achieves comparable map fidelity with up to 94x lower memory overhead than prior works. Ultimately, GEVO facilitates the design of ASIC accelerators for real-time, high-fidelity, and low-energy reconstruction on mobile devices.

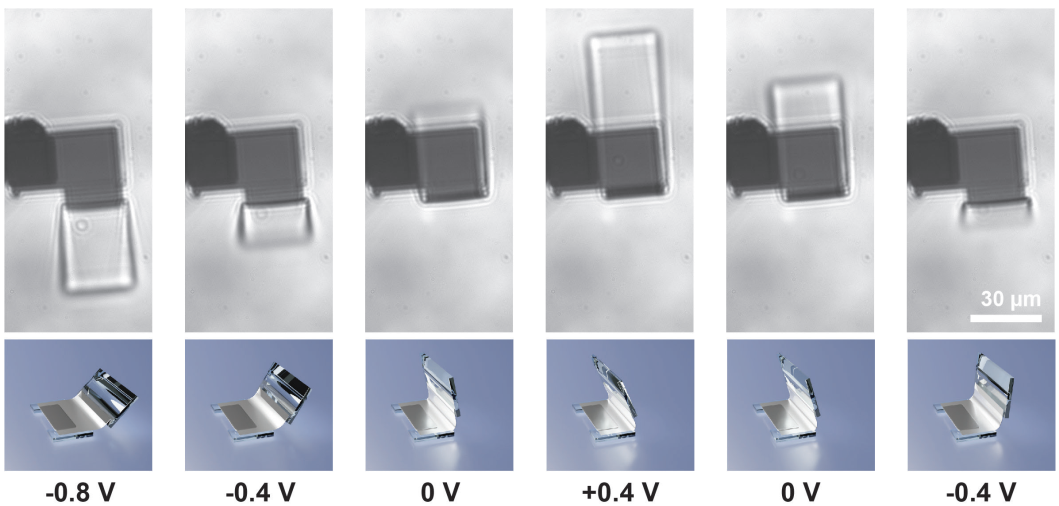
(a) Reconstruction before catastrophic forgetting | (b) MonoGS no past images 8 images stored (7 MB) | (c) GEVO (This work) 8 images stored (7 MB) | (d) MonoGS 114 images stored (100 MB)

▲ Figure 1: The region (a) catastrophically forgets (b) when no past images are used to retrain. GEVO (d) maintains high fidelity with significantly lower memory overhead for storing images compared with prior work (c).

Ultra-thin Ruthenium Electrochemical Actuators

Z. Zheng, M. F. Reynolds, J. Clark, S. Norris, Q. Liu, N. L. Abbott, I. Cohen, P. L. McEuen
Sponsorship: Cornell Center for Materials Research (DMR-1719875)

Electrochemical micro-actuators are essential components in micro-robotics, micro-fluidics, and biomedical devices. The surface electrochemical actuator (SEA) platform was developed by our group with atomic layer deposited (ALD) platinum and shown to provide locomotion in CMOS integrated micro-scale robots. Prior to the SEAs, there had been a lack of micron-scale actuator systems that can be processed with the standard semiconductor technology and well-integrated with on-board CMOS for control. Besides platinum, materials with similar properties have the potential to accomplish comparable functions and may possess advantageous properties like higher force output or better durability. In this work, we investigate such actuators of nano-scale thickness fabricated with ALD ruthenium. Similar to the platinum version, these actuators operate at low-voltages, low-power, with high durability, and ample force output, while being entirely compatible with industrial standard microelectronics processing. Distinguishingly, though, these actuators show atomic layer etching (ALE) when driven at certain higher voltages, which allows us to have special control over the precise thickness and thereby motions of these actuators. Thus, we show ruthenium as a viable option for electrochemical micro-actuators with unique additional features.

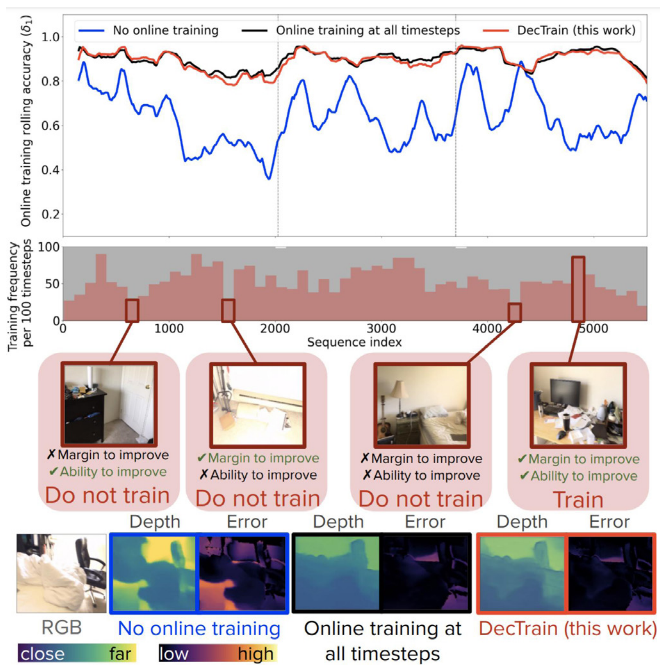


▲ Figure 1: A sequence of optical images and schematics showing an actuator's motion in a 1 Hz sweep cycle between +0.4 and -0.8 V.

DecTrain: Deciding When to Train a Monocular Depth DNN Online

Z.-S. Fu, S. Sudhakar, S. Karaman, V. Sze
Sponsorship: NSF, Real-Time Machine Learning Program Grant no. 1937501, MIT-Accenture Fellowship, Huang Phillips Fellowship, Gift from Intel

Monocular depth deep neural network (DNN) is useful for 3D reconstruction by predicting per-pixel depth of an RGB image. While using a monocular depth DNN can be more energy efficient and has a smaller form factor than traditional bulky and high-power physical depth sensors, it can deteriorate in accuracy when deployment data differs from training data. While performing online training at all timesteps can improve accuracy, it is computationally expensive. We propose DecTrain, a new algorithm that decides when to train a monocular depth DNN with self-supervision by comparing the cost of training with the predicted accuracy gain. DecTrain maintains accuracy compared to online training at all timesteps on out-of-distribution data, while training only 44% of the time on average. We also compare the recovery of a low inference cost DNN using DecTrain and a more generalizable high inference cost DNN, and find DecTrain recovers the majority (97%) of the accuracy gain of online training at all timesteps while reducing computation compared to the high inference cost DNN which recovers only 66%. DecTrain enables low-cost online training for a smaller DNN to have competitive accuracy with a larger DNN at a lower overall computational cost.



▲ Figure 1: Compared to the baseline of online training at all timesteps (black) or no timesteps (blue), DecTrain (red) maintains the accuracy improvement of adaptation while training on only a subset of the timesteps.

Flexible Acoustically Active Surfaces Based on Piezoelectric Microstructures

T. Dang, J. Han, Z. Zheng, J. H. Lang, V. Bulović

Flexible acoustic transducers have gained significant attention due to their diverse applications in modern technologies, including active noise control, human-machine interfaces, ultrasonic imaging, and tactile sensing. Flexible speakers typically utilize electrostatic or piezoelectric effects to generate sound, with piezoelectric loudspeakers standing out for their ease of fabrication and low power consumption. Despite their advantages, most demonstrated flexible speakers show limited performance or require high operating voltages, restricting their practical use in applications involving potential human contact.

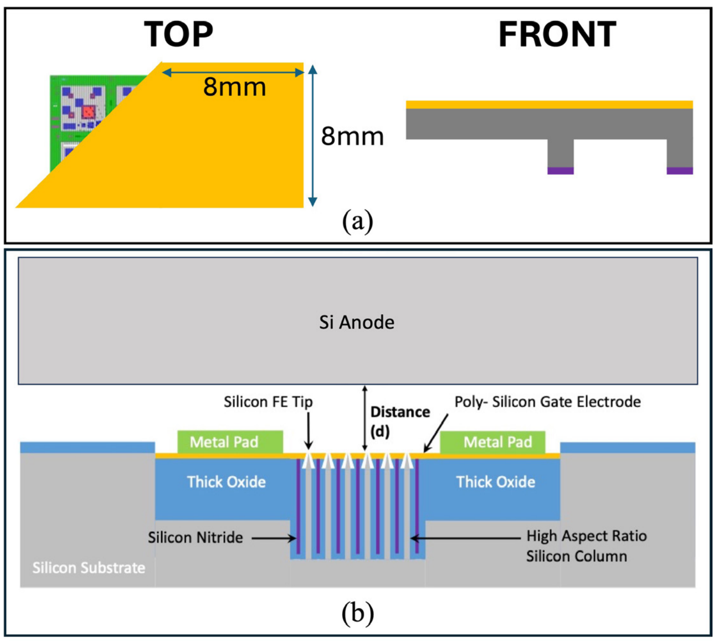
In this project, we develop a flexible thin-film acoustic transducer based on an ensemble of free-standing microstructures using a piezoelectric polyvinylidene fluoride (PVDF) sheet, targeting potential wearable applications. The PVDF microstructure arrays are encapsulated between two layers of flexible substrates that not only protect the piezoelectric microstructures but also define their shapes while allowing free vibration. The performance evaluation of these speakers demonstrates excellent sound generation, achieving 60 dB at 1 kHz under 20V excitation. The speakers display broad bandwidths reaching up to 100 kHz, thanks to the high resonant frequencies of the fabricated microstructures. Additionally, the device consumes power at the milliwatt level, offering a substantial efficiency advantage over dynamic and thermoacoustic loudspeakers. Therefore, this lightweight, flexible and low-cost speaker could perform as an innovative interface for acoustic applications.

Anode Engineering to Reduce On-Resistance of Field Emitter Arrays

Y. Shin, W. Chern, N. Karaulac, A. I. Akinwande
Sponsorship: AFOSR

Field emitter arrays (FEAs) are promising electron sources for high-power and high-frequency devices such as power switches and electric jet propulsion. The property of ballistic transport and high breakdown field make FEAs capable of low switching losses and on-resistance. However, prior optimization methods fail to account for changes in electrostatics along the vacuum channel due to the anode geometry and position, causing unfavorable phenomena in device characteristics.

In this work, we attempt to engineer the anode of FEAs, specifically for anodes configured with anode-to-emitter distances of 100m, using a MEMS fabricated silicon anode for on-chip integration. We find that the geometry and position of the anode improves the space charge limited (triode) regime of the FEA output characteristics, achieving lower on-resistance. These results pave a way to integrate FEAs into compact high-power switches for megawatt operation with comparable on-resistances with GaN and SiC.



▲ Figure 1: (a) Anode design of three layers consisting of silicon oxide (purple), silicon (gray), and TiAu (gold). The relative size of the flat anode is compared to a sample device chip. (b) Schematic of the experimental setup relative to the device.