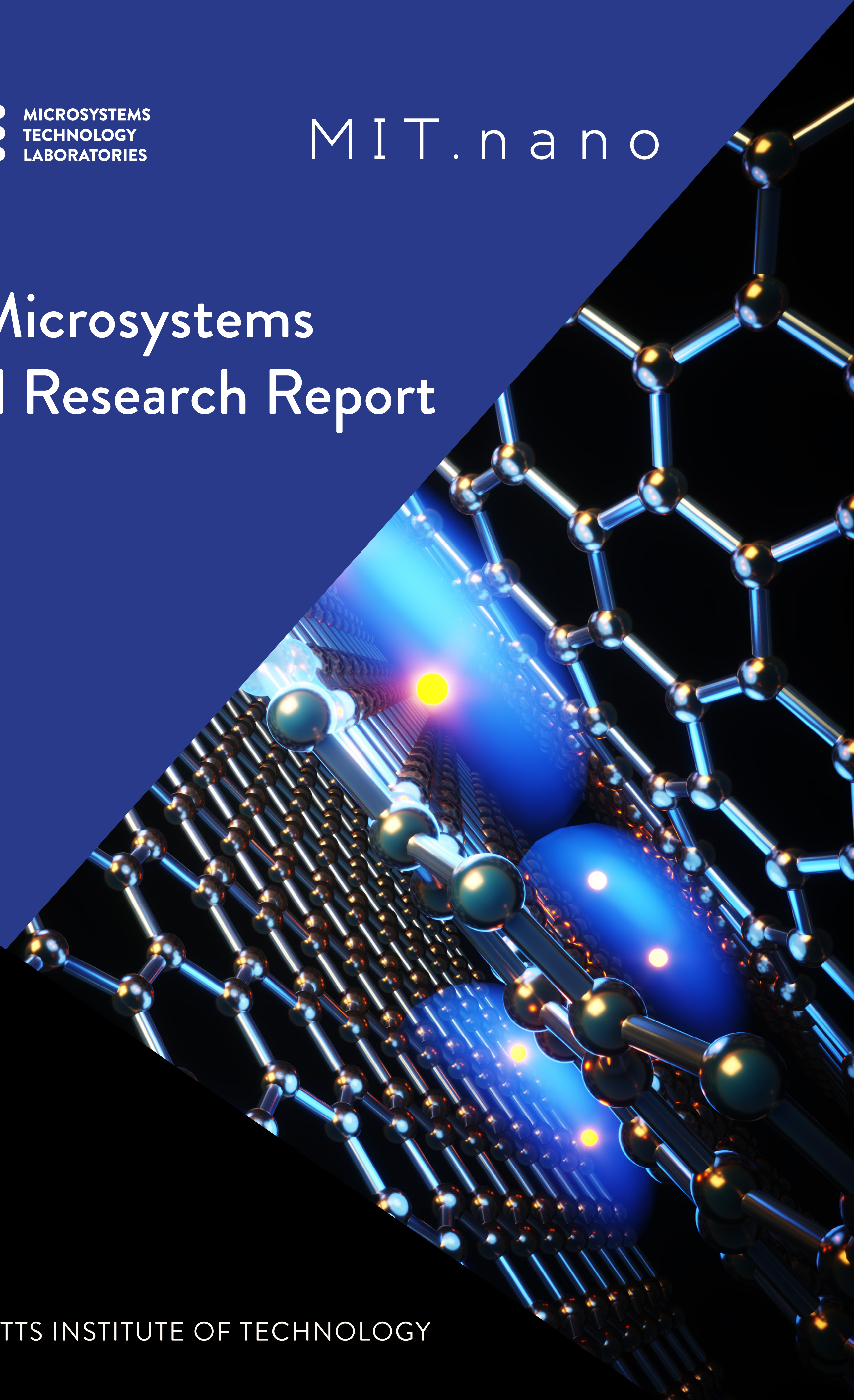
MTL MICROSYSTEMS TECHNOLOGY LABORATORIES

MIT.nano

2021 Microsystems Annual Research Report



MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Rethinking Plant-Based Materials Production: Selective Growth of Tunable Materials via Cell Culture

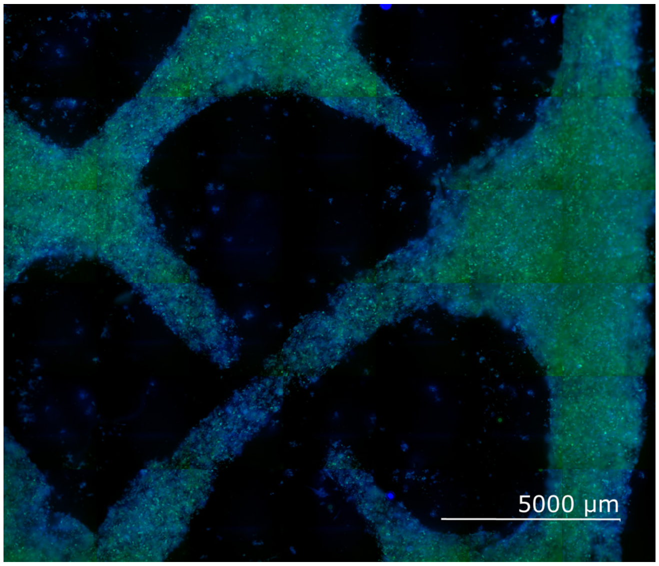
A. L. Beckwith, J. T. Borenstein, L. F. Velásquez-García

Sponsorship: Draper Fellowship Program

Current systems for plant-based materials production are inefficient and place unsustainable demands on environmental resources. Traditionally cultivated crops present low yields of industrially useful components and require extensive post-harvest processing to remove extraneous portions of the plants. Large-scale monoculture remains the unchallenged standard for biomass production despite the negative impacts of the practice to the surrounding biome as well as a susceptibility to season, climate, and local resource availability. This work proposes a novel solution to these shortcomings based on the selective cultivation of useful, tunable plant tissues using scalable, land-free techniques. By limiting biomass cultivation to only desirable plant tissues, ex planta farming promises to improve yields while reducing plant waste and competition for arable land.

Employing a *Zinnia elegans* model system, we provide the first proof-of-concept demonstration of isolated, tissue-like plant material production by way of gel-mediated cell culture. Parameters governing cell development and morphology including hormone concentrations, medium pH, and initial cell density are optimized and implemented to demonstrate the tunability of cultured biomaterials at cellular and macroscopic scales. Targeted deposition of cell-doped, nutrient-rich gel scaffolds via injection molding and 3D bioprinting enable biomaterial growth in near-final form (Figure 1), reducing downstream processing requirements. These investigations demonstrate the implementation of plant cell culture in a new application space, propose novel methods for quantification and evaluation of cell development, and characterize morphological developments in response to critical culture parameters—illustrating the feasibility and potential of the proposed techniques.

The proposed concept of selectively grown, tunable plant materials via gel-mediated cell culture is believed to be the first of its kind. This work uniquely quantifies and modulates cell development of cultured primary plant products to optimize and direct growth of plant materials.



▲Figure 1: Bioprinted culture, with vascular cell types, grown to confluency.

FURTHER READING

- A. L. Beckwith, J. T. Borenstein, and L. F. Velásquez-García, “Tunable Plant-based Materials via *In Vitro* Cell Culture Using a *Zinnia Elegans* Model,” *J Cleaner Production*, vol. 288, pp. 125571, Mar. 2021., DOI: 10.1016/j.jclepro.2020.125571.
- A. L. Beckwith, J. T. Borenstein, and L. F. Velásquez-García, “Monolithic, 3D-printed Microfluidic Platform for Recapitulation of Dynamic Tumor Microenvironments,” *J Microelectromech* Syst, vol. 27, 6, pp.1009-1022, Oct. 2018, DOI: 10.1109/JMEMS.2018.2869327.
- A. L. Beckwith, L. F. Velásquez-García, and J. T. Borenstein, “Microfluidic Model for Evaluation of Immune Checkpoint Inhibitors in Human Tumors,” *Advanced Healthcare Materials*, vol. 8, 11, pp. 1900289, Jun. 2019, DOI: 10.1002/adhm.201900289.

Advanced Microfluidic Heat Exchangers via 3D Printing and Genetic Algorithms

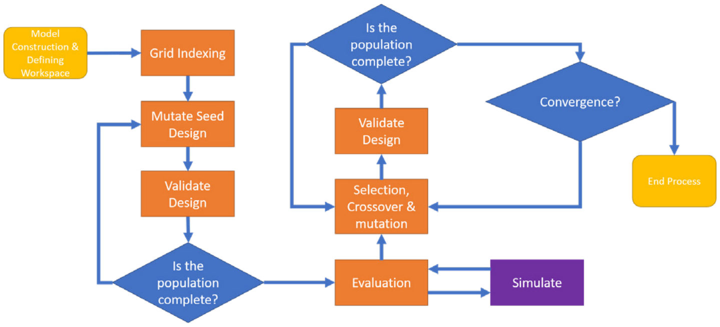
J. Izquierdo-Reyes, L.F. Velásquez-García

Sponsorship: MIT-Tecnologico de Monterrey Nanotechnology Program

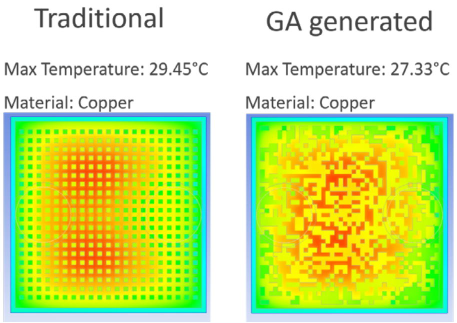
Power electronics are fundamental in many high-tech applications, e.g., electric cars. Adequate heat dissipation of these electronic components is essential for them to operate properly and attain long lifespans. Cooling high-power electronics typically employs heat exchangers that put a liquid in contact with hot surfaces to extract heat. Using microfluidics can greatly increase the surface-to-volume ratio of the liquid, boosting heat transfer. However, classically designed heat exchangers do not properly address the non-uniformity of the heat field, e.g., localized hot spots. In addition, better power microelectromechanical system microfluidics can be created via additive manufacturing, involving better materials and implementing more effective geometries than in mainstream cleanroom microfabrication. In particular, metal 3D printing can monolithically create complex microfluidic devices while greatly simplifying the manufacturing process and requiring significantly less time than subtractive manufacturing.

Genetic algorithms (GAs) can be used to implement an iterative design process inspired in natural selection that can potentially create better engineering solutions by generating unexpected implementations. In a nutshell, GAs are used to create multiple generations of randomized mutations of the parent designs (called subjects), looking to optimize the solution's performance by minimizing/maximizing a particular fitness function.

In this project, we are exploring metal 3D printing and GAs to implement better microfluidic heat exchangers. The fitness function employed ponders trade-offs between temperature and pressure drop in the cold plate to minimize the maximum temperature. We use a finite element solver with a computational fluid dynamics module to obtain solutions of the flow and temperature fields of each subject of each generation and then we used software to compare their performance across each generation and down-select the best designs. The software creates and analyzes new generations until it attains a certain threshold value in the fitness function (Figure 1). The resultant devices are complex, often counter-intuitive, and unlikely to be synthesized by a human using first principles (Figure 2), surpassing the performance of traditional designs.



▲Figure 1: Block diagram of the algorithm employed to design advanced microfluidic heat exchangers.



▲Figure 2: Classically designed (left) and GA-designed (right) finned cold plate for a CPU chip. A reduction of 2.12 °C in the maximum device temperature was attained.

FURTHER READING

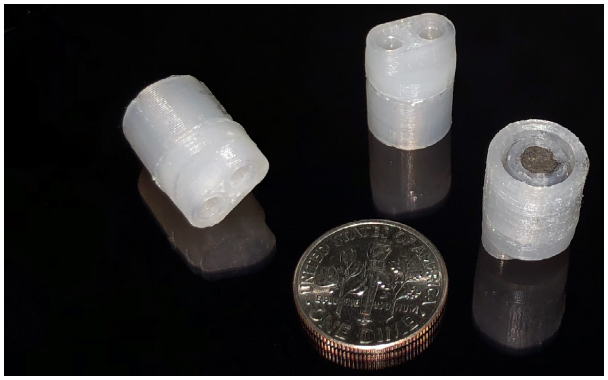
- E. Segura-Cárdenas and L. F. Velásquez-García, "Additively Manufactured Robust Microfluidics via Silver Clay Extrusion," *J. Microelectromech. Syst.*, vol. 29, no. 3, pp. 427-437, Jun. 2020.
- Z. Sun and L. F. Velásquez-García, "Monolithic FFF Printed, Biodegradable, Biocompatible, Dielectric–Conductive Microsystems," *J. Microelectromech. Syst.*, vol. 26, no. 6, pp. 1356- 1370, Dec. 2017.
- A. L. Beckwith, J. T. Borenstein, and L. F. Velásquez–García, "Monolithic, 3D-printed Microfluidic Platform for Recapitulation of Dynamic Tumor Microenvironments," *J. Microelectromech. Syst.*, vol. 27, pp. 1009-1022, Oct. 2018.

3D-Printed Miniature Vacuum Pumps

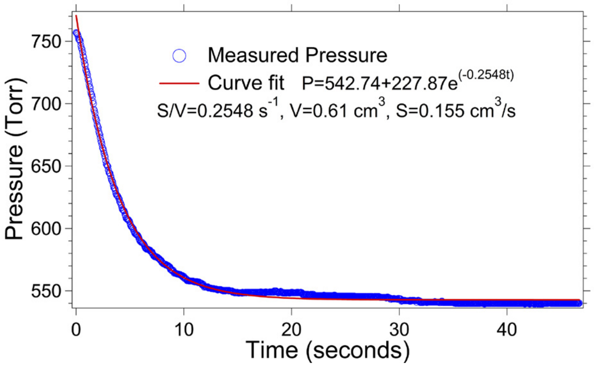
A. P. Taylor, J. Izquierdo-Reyes, L.F. Velásquez-García
Sponsorship: Edwards Vacuum, MIT-Tecnologico de Monterrey Nanotechnology Program

Compact pumps that create and sustain vacuum environments while supplying precise gas flow rates are essential to implement a variety of microsystems. Positive displacement vacuum pumps, e.g., diaphragm pumps, create and maintain vacuum by cycling pockets of gas that are compressed from rarified conditions to atmospheric pressure. Miniaturized positive displacement vacuum pumps typically have dead volumes very similar to the maximum displacement of their compression chambers, resulting in the creation of modest vacuums.

Magnetic, long-stroke actuators could be used to implement pump chambers with large compression ratios; an exciting possibility to implement such actuators at a low cost is additive manufacturing. In this project, we demonstrated the first miniaturized, additively manufactured, magnetic diaphragm pumps for liquids in the literature where all constitutive parts, including the magnets, are monolithically 3D-printed. The devices were created in nylon-based feedstock via fused filament fabrication, in which thermoplastic filament was extruded from a hot nozzle to create a solid object layer by layer. The miniature pumps use 150-µm- or 225-µm- thick membranes connected to a piston with an embedded magnet, a chamber, two diffusers, and two fluidic connectors (Figure 1). We also experimentally observed that the same pumps for liquids can be used as vacuum pumps if they are first moistened with a small amount of water to enable the pump diffusers to seal during actuation. The miniature 3D-printed pumps can attain an ultimate pressure of 540 Torr at an operating frequency of 230 Hz, i.e., the pumps achieve a pressure of 220 Torr below atmospheric pressure (Figure 2). The ultimate pressure achieved by our pumps is close to values reported from commercially available, non-microfabricated, miniature diaphragm pumps with comparable diaphragm diameters. We speculate that changing the design of the pump chamber to increase its compression ratio and printing a more flexible and compliant material could attain lower ultimate pressure.



▲ Figure 1: 3D-printed miniature magnetic pumps next to a US dime; the fluidic ports and the embedded magnet are visible at either end of the pumps.



▲ Figure 2: Pressure versus time characteristic of a 3D-printed magnetic pump (from A. P. Taylor, J et al., J. Phys. D: Appl. Phys., vol. 53, no. 35-5002, Jun. 2020). Data in blue, exponential curve fit in red.

FURTHER READING

- A. P. Taylor, C. Velez Cuervo, D. P. Arnold, and L. F. Velásquez–García, "Fully 3D-printed, Monolithic, Mini Magnetic Actuators for Low-cost, Compact Systems," *J. Microelectromech. Syst.* vol. 28, no. 3, pp. 481–493, Jun. 2019.
- A. P. Taylor and L. F. Velásquez-García, "Miniaturized Diaphragm Vacuum Pump by Multi-Material Additive Manufacturing," *J. Microelectromech. Syst.*, vol. 26, no. 6, pp. 1316 – 1326, Dec. 2017.
- A. P. Taylor, J. Izquierdo-Reyes, and L. F. Velásquez–García, "Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases," *J. Phys. D: Appl. Phys.*, vol. 53, no. 35-5002, Jun. 2020.

3D-Printed, Miniaturized Retarding Potential Analyzers for Cubesat Ionospheric Studies

J. Izquierdo-Reyes, L.F. Velásquez-García

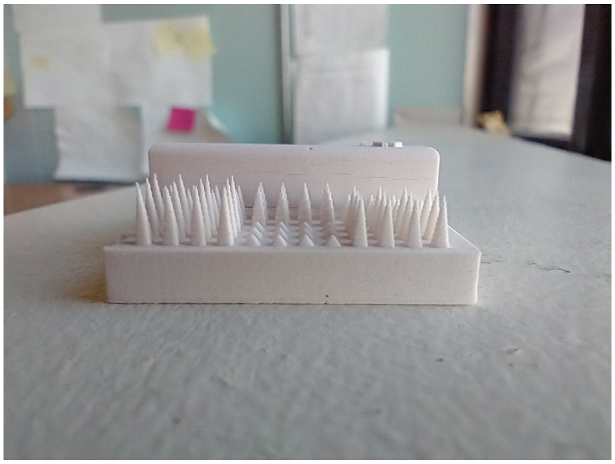
Sponsorship: MIT-Portugal, MIT-Tecnologico de Monterrey Nanotechnology Program

The ionosphere is an upper region of the atmosphere that is made of plasma created and sustained by solar UV radiation. Little is known about some of the layers of the ionosphere, e.g., the thermosphere. Comprehending the processes taking place in the thermosphere is essential to understand local and global weather and global warming. There is evidence that global warming is cooling down the thermosphere, causing serious issues, e.g., variation in satellites' drag and less recycling of water. In-situ data would provide more and better information.

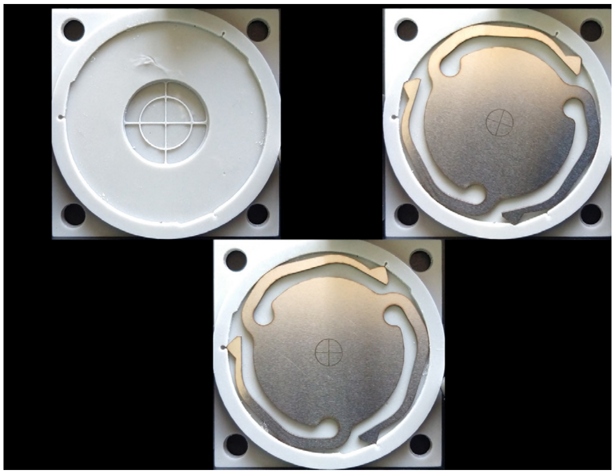
Plasma sensors are used to characterize plasmas, measuring one or more properties that can be derived from the position and velocity distributions of the particles that make up the plasma. A retarding potential analyzer (RPA) is a multi-gridded sensor that measures the ion energy distribution of a plasma. In an RPA, the diameter of the apertures of the outermost grid (the floating grid) measures up to two Debye lengths to trap the plasma outside the sensor while the inter-grid spacing measure up to four Debye lengths to avoid space charge effects that would smear the measurements. The Debye length in the ionosphere is about 1 mm.

Sending hardware to space is quite expensive because, among other reasons, of the physics of rocket propulsion, e.g., requiring ejecting propellant many times the mass of the spacecraft. Therefore, technologies that yield smaller, lighter, and cheaper space hardware without sacrificing performance are of great interest. Consequently, there is great interest in developing mission-focused miniaturized satellites, i.e., cubesats (1-10 Kg, a few L in volume).

In this project we are harnessing additive manufacturing to demonstrate better and cheaper cubesat plasma sensors. Our RPA design uses laser-micromachined stainless steel grids integrated to a 3D-printed ceramic housing made via vat polymerization using 60-µm by 60-µm by 100-µm XYZ voxels (Figure 1). Each grid is assembled to the housing using a set of engineered springs that provide active alignment. Experiments show that the per-level assembly precision is better than 100 µm (Figure 2). Inter-grid alignment results in larger current signals. Current work focuses on completing, fabricating, and characterizing the RPA design.



▲Figure 1: Example of a 3D-printed ceramic resolution matrix. The width of the piece facing the camera is about 60 mm.



▲Figure 2: Selected views of an assembly misalignment experiment: a) ceramic grid holder with spring interacting features, b) metallic grid before spring actuation, c) metallic grid with actuated and locked-in springs.

FURTHER READING

- E. Heubel and L. F. Velásquez–García, "Microfabricated Retarding Potential Analyzers with Enforced Aperture Alignment for Improved Ion Energy Measurements in Plasmas," *J. Microelectromech. Syst*. vol. 24, no. 5, pp. 1355-1369, 2015.
- Z. Sun, G. Vladimirov, E. Nikolaev, and L. F. Velásquez-García, "Exploration of Metal 3-D Printing Technologies for the Microfabrication of Freeform, Finely Featured, Mesoscaled Structures," *J. Microelectromech. Syst*., vol. 27, no. 6, pp. 1171 – 1185, Dec. 2018
- C. Yang and L. F. Velásquez-García, "Low-Cost, Additively Manufactured Electron Impact Gas Ionizer with CNT Field Emission Cathode for Compact Mass Spectrometry," *J. Phys. D – Appl. Phys*. vol. 52, no. 7, 075301 (9pp), Feb. 2019.

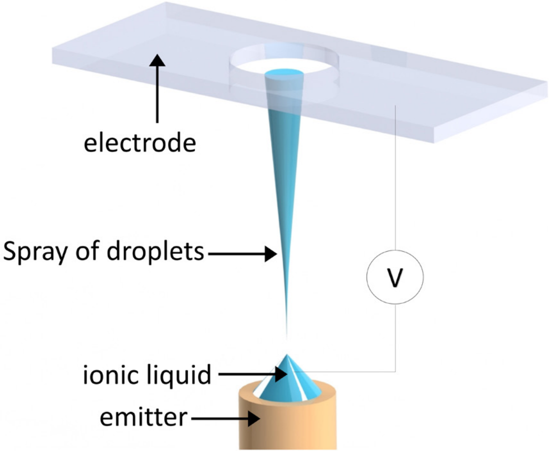
Internally Fed, Additively Manufactured Electrospray Thruster

H. Kim, L. F. Velásquez-García
Sponsorship: MIT Portugal

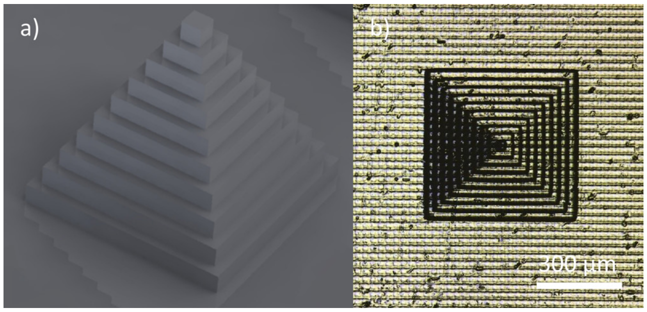
Electrospray engines produce thrust by electrohydrodynamically ejecting high-speed ions or droplets. Electrospray emitters work better if miniaturized because their start-up voltage decreases with the square root of the emitter diameter. A single emitter has very low thrust; multiplexing the emitters, so they uniformly operate in parallel, makes it possible to increase the thrust delivered. Electrospray thrusters are typically created via precision subtractive manufacturing techniques, which is time-consuming and expensive. For New Space, i.e., the development of a commercial space industry, additive manufacturing is an attractive possibility to create complex hardware that is inexpensive and exquisitely iterated and optimized.

Our group recently demonstrated the first additively manufactured ionic liquid electrospray thrusters in the literature; these devices attain pure ion emission in both polarities, maximizing their specific impulse. However, the propellant flow rate, which has an upper bound for pure ionic emission, limits the thrust per emitter that can be attained for a given bias voltage. An engine that can deliver larger per-emitter thrust, at the expense of using less efficiently the propellant, is of interest for impulsive maneuvers.

Consequently, we are also interested in developing additively manufactured, low-specific impulse, high per-emitter thrust electrospray engines. Unlike the externally fed, nanoporous fluidic structure used in the ionic thrusters previously described, an internally fed emitter architecture is a better fit to produce droplets (Figure 1), which are heavier than ions, resulting in higher per-emitter thrust. We use the vat polymerization method called digital light processing to make emitters with narrow channels that provide high hydraulic resistance. Using resolution matrices drawn in ~25 µm voxels and a resin chemically resistant to an ionic liquid, we verified the high fidelity of the printed parts to the computer-aided design (CAD) models (Figure 2). Current research efforts focus on exploring the resolution limits of the printable feedstock for solid and negative features and developing device designs with hydraulic networks that provide a high and uniform hydraulic impedance to each emitter.



▲ Figure 1: Schematic of a single internally fed electrospray emitter.



▲ Figure 2: a) CAD image and b) confocal micro-scope image of printed part for one of the test structures used to verify printing fidelity.

FURTHER READING

- F. A. Hill, E. V. Heubel, P. P. de Leon, and L. F. Velásquez-García, "High-Throughput Ionic Liquid Ion Sources Using Arrays of Microfabricated Electrospray Emitters with Integrated Extractor Grid and Carbon Nanotube Flow Control Structures," *J. of Microelectromechanical Systems*, vol 23. no. 5, pp. 1237-1248, May. 2014.
- D. Olvera-Trejo and L. F. Velásquez-García, "Additively Manufactured MEMS Multiplexed Coaxial Electrospray Sources for High-Throughput, Uniform Generation of Core-Shell Microparticles," *Lab on a Chip*, vol. 16, no. 21, pp. 4121-4132, Oct. 2016.
- D. V. Melo Maximo, and L. F. Velásquez-García, "Additively Manufactured Electrohydrodynamic Ionic Liquid Pure-Ion Sources for Nanosatellite Propulsion," *Additive Manufacturing*, vol. 36, p. 101719, Dec. 2020.

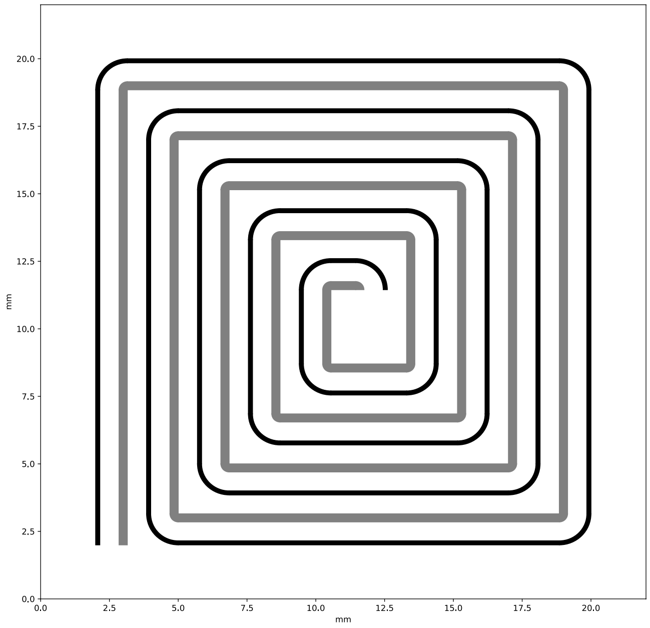
Planar Field-Emission Electron Sources via Direct Ink Writing

N. Klugman, L. F. Velásquez-García
Sponsorship: MIT Portugal

Vacuum electron sources appear in numerous technologies, from microscopy to displays to mass spectrometry. The two main forms vacuum electron sources can take are thermionic and field emission. Thermionic sources emit electrons by raising the temperature of a conductor so that many of its electrons have an energy greater than the potential barrier trapping them, allowing them to escape. Field-emission sources use an applied electric field to lower the potential barrier, allowing electrons to quantum tunnel out of the conductor. Field-emission sources can therefore operate at lower temperatures, in a poorer vacuum, faster, and using less energy, all of which increase the usability of the electron source.

Field-emission sources' emitting electrodes have been made from many materials, but research has focused on carbon nanotubes (CNTs). CNTs' nanosized tips and high aspect ratio lead to high electric fields at modest voltages, which is useful since the emitted current increases with electric field; in addition, CNTs have excellent chemical resistance, e.g., resisting oxidation by the trace gases in the vacuum. Manufacturing CNT field-emission sources is often a costly and time-intensive effort, particularly when the CNT growth locations are restricted by desired device geometry.

To affordably implement CNT field emission cathodes, this project explores direct ink writing to create in-plane, gated field-emission sources. A spiral CNT ink trace is printed on an insulating substrate, along with a symmetric, co-planar trace (see Figure 1) of a different conducting (e.g., silver nanoparticle) ink. A voltage applied between the traces induces an electric field, causing electron tunneling from the CNT tips. The planar design reduces manufacturing complexity and increases electron transmission. Current work includes printable feedstock material selection, exploration of geometric modifications to increase device longevity, and increasing imprint density to allow for greater emission current density.



◀Figure 1: Computer-aided design of 3D-printed field-emission cathode with in-plane gate.

FURTHER READING

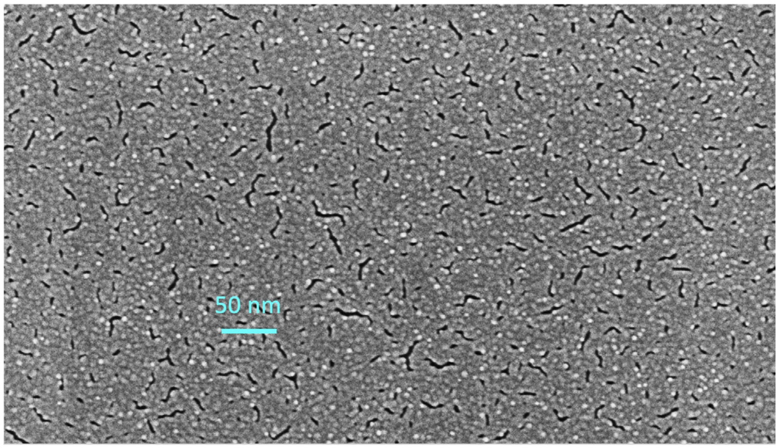
- A. Perales and L. F. Velásquez-García, "Fully 3D-Printed Carbon Nanotube Field Emission Electron Sources with In-plane Gate Electrode," *Nanotechnology*, vol. 30, no. 49, p. 495302, Dec. 2019
- C. Yang and L. F. Velásquez-García, "Low-cost, Additively Manufactured Electron Impact Gas Ionizer with CNT Field Emission Cathode for Compact Mass Spectrometry," *Journal of Physics D – Applied Physics*, vol. 52, no. 7, p. 075301, Feb. 2019.
- L. F. Velásquez-García, A. I. Akinwande, and M. Martínez-Sánchez, "Precision Hand Assembly of MEMS Subsystems Using DRIE-patterned Deflection Spring Structures: An Example of an Out-of-Plane Substrate Assembly," *Journal of Microelectromechanical Systems*, vol. 16, no. 3, pp. 598 – 612, Jun. 2007.

Nanoparticle-Enhanced Microsputtered Gold Thin Films for Low-Cost, Agile Manufacturing of Interconnects

Y. Kornbluth, R. Mathews, L. Paramswaran, L. Racz, L.F. Velásquez-García
Sponsorship: US Air Force

Silicon and gold are ubiquitous in the microelectronics industry—silicon as the cornerstone of semiconductor devices, and gold as a material with unmatched electro-optical properties. However, gold films do not adhere well to silicon or silicon dioxide, necessitating the need for an adhesion layer made of a third material. This need increases complexity and cost. Also, reworking interconnects via traditional (cleanroom) technology poses challenges, e.g., thermal budget, vacuum compatibility.

In this project, we explore microplasma sputtering to implement at low-cost interconnects for agile electronics. We have shown that under proper operational conditions, a microplasma sputterer creates at room temperature and atmospheric pressure dense, highly conductive gold films with a fivefold better adhesion than the state of the art, without using an adhesion layer, annealing, or any other pre/post printing steps. If the gold film is sputtered in an atmospheric-pressure microsputterer in the presence of a fast-moving jet of air, gold nanoparticles form. The high collisionality of the atmospheric-pressure gas and high energy of the plasma facilitate nanoparticle formation, while the jet carries the nanoparticles to the substrate. The speed of the jet of air determines the size of the nanoparticles. These nanoparticles then act as an adhesion layer to allow a gold film, made of these nanoparticles and individual atoms, to adhere well to a silicon or silicon dioxide substrate. By rastering the printhead over the desired deposition area, we can interweave large nanoparticles and smaller atoms, creating a dense film (Figure 1). This process allows us to optimize adhesion, density, and conductivity simultaneously. Conductivity of the resultant films is also near-bulk (120% of bulk gold—the highest value reported for a room-temperature additive manufacturing method), allowing for their use in microelectronics.



▲ Figure 1: SEM micrograph of microsputtered gold imprint (from Kornbluth et al., Additive Manufacturing, vol. 36, p. 101679, Dec. 2020). The film is dense, highly electrically conductive and is made of the agglomeration of nanoparticles created in the plume of a room-temperature, atmospheric pressure microsputterer.

FURTHER READING

- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. M. Racz, and L. F. Velásquez-García, "Nano-additively Manufactured Gold Thin Films with High Adhesion and Near-bulk Electrical Resistivity via Jet-assisted Nanoparticle-dominated, Room-temperature Microsputtering," *Additive Manufacturing*, vol. 36, p. 101679, Dec. 2020.
- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. M. Racz, and L. F. Velásquez-García, "Room-temperature, Atmospheric-pressure Microsputtering of Dense, Electrically Conductive, Sub-100 nm Gold Films," *Nanotechnology*, vol. 30, no. 28, p. 285602, Apr. 2019.
- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. M. Racz, and L. F. Velásquez-García, "Microsputterer with Integrated Ion-drag Focusing for Additive Manufacturing of Thin, Narrow Conductive Lines," *Journal of Physics D – Applied Physics*, vol. 51, no. 16, p. 165603, Apr. 2018.

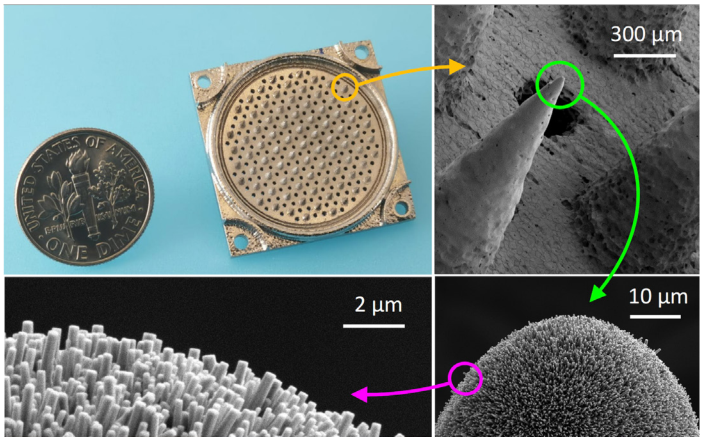
Additively Manufactured Electrospray Ion Thrusters for Cubesats

D. Melo-Máximo, L. F. Velásquez-García
Sponsorship: MIT Portugal, MIT-Tecnologico de Monterrey Nanotechnology Program

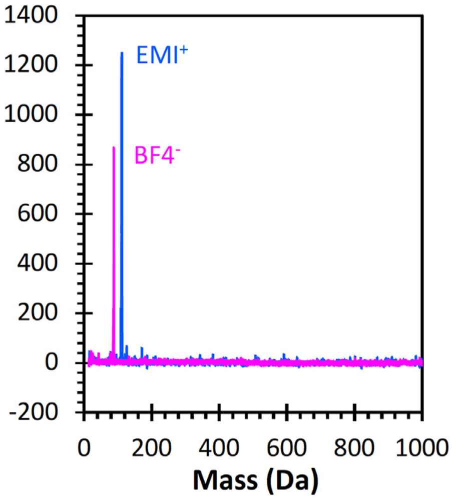
Putting satellites in orbit is very expensive: typical rocket launches cost up to hundreds of millions of US dollars, and typical per-kilogram of payload costs are up to tens of thousands of US dollars). Therefore, great interest exists to develop smaller, lighter, and cheaper space satellites with adequate performance. In particular, since the 1990s, research groups across the world have been developing and launching cubesats, i.e., 1-10 Kg, a few L in volume, miniaturized, mission-focused satellites. Multi-material additive manufacturing is of great interest for fabricating cubesats, as it can monolithically create complex, multi-functional objects composed of freeform components made of materials matched to performance.

Electrospray engines produce thrust by electrohydrodynamically ejecting charged particles from liquid propellant. Electrospray thrusters are an attractive choice for propelling cubesats because their physics favors miniaturization, e.g., their start-up voltage scales with the square root of the emitter diameter. The thrust of an electrospray emitter is very low; thus , electrospray engines have large arrays of emitters to greatly boost the thrust they can deliver.

We recently demonstrated the first additively manufactured electrospray engines. Our devices are composed of large arrays of conical emitters coated by a conformal forest of zinc oxide nanowires (ZnONWs) that transport the propellant to the emitter tips (Figure 1). The ZnONWs provide a large hydraulic impedance that regulates and uniformizes the flow across the emitter array, restricting the flow rate per emitter to attain ionic emission. Our devices are also remarkable because, unlikely all the other electrospray ionic liquid engines reported in the literature, they emit only ions using the ionic liquid EMI-BF_4 as propellant (Figure 2), which maximizes their specific impulse for a given bias voltage, i.e., they produce more thrust per unit of propellant flow rate. Current work focuses on optimizing device design and fabrication and on developing a multi-electrode stack to control the plume.



▲Figure 1: From the top left, clockwise: an additively manufactured electrospray array next to a U.S. dime, close-up of emitters, close-up of an emitter tip, close-up of the ZnONW forest.



▲Figure 2: Mass spectra of emitted plume using EMI-BF4 as propellant. In both polarities, the plume is composed exclusively of ions.

FURTHER READING

- F. A. Hill, E. V. Heubel, P. P. de Leon, and L. F. Velásquez-García, "High-Throughput Ionic Liquid Ion Sources Using Arrays of Microfabricated Electrospray Emitters with Integrated Extractor Grid and Carbon Nanotube Flow Control Structures," *J. Microelectromech. Syst.*, vol. 23, no. 5, pp. 1237-1248, May 2014.
- D. Olvera-Trejo and L. F. Velásquez-García, "Additively Manufactured MEMS Multiplexed Coaxial Electrospray Sources for High-Throughput, Uniform Generation of Core-Shell Microparticles," *Lab Chip*, vol. 16, no. 21, pp. 4121-4132, Oct. 2016.
- D. V. Melo Maximo and L. F. Velásquez-García, "Additively Manufactured Electrohydrodyna- mic Ionic Liquid Pure-Ion Sources for Nanosatellite Propulsion," *Additive Manufacturing*, vol. 36, p. 101719, Dec. 2020.

Luis Fernando Velásquez-García

Principal Research Scientist
Microsystems Technology Laboratories

Micro- and nano-enabled, multiplexed, scaled-down systems that exploit high electric field phenomena; powerMEMS; additively manufactured MEMS/NEMS. Actuators, cold cathodes, ionizers, microfluidics, microplasmas, CubeSat hardware, portable mass spectrometry, pumps, sensors, X-ray sources.

Rm. 39-415B | 617-253-0730 | lfvelasq @ mit . edu

GRADUATE STUDENTS

Ashley L. Beckwith, MechE
Alejandro Diaz, EECS
Alex Kashkin, MechE
Nicholas Klugman, EECS
Hyeonseok Kim, MechE
Yosef S. Kornbluth, MechE
Zackary Pitcher, EECS

UNDERGRADUATE STUDENTS

Andrea Garcia, MechE
Maisha Prome, BioEng
Jordan Street, Wellesley

VISITOR

Javier Izquierdo Reyes, Tecnológico de Monterrey

SUPPORT STAFF

Jami L. Mitchell, Administrative Assistant

SELECTED PUBLICATIONS

L. F. Velásquez-García and Y. Kornbluth, “Biomedical Applications of Metal 3D Printing,” accepted for publication, *Annual Review of Biomedical Engineering*, 2021.

A. L. Beckwith, J. Borenstein, and L. F. Velásquez-García, “Tunable Plant-based Biomaterials via in vitro Cell Culture using a Zinnia elegans Model,” *Journal of Cleaner Production*, vol. 288, 125571 (10pp), Mar. 2021.

D. Melo Máximo and L. F. Velásquez-García, “Additively Manufactured Electrohydrodynamic Ionic Liquid Pure-Ion Sources for Nanosatellite Propulsion”, *Additive Manufacturing*, vol. 36, 101719 (11pp), Dec. 2020.

Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. Racz, and L. F. Velásquez-García, “Nano-Additively Manufactured Gold Thin Films with High Adhesion and Near-Bulk Electrical Resistivity via Jet-Assisted, Nanoparticle-Dominated, Room-Temperature Microsputtering,” *Additive Manufacturing*, vol. 36, 101679 (11pp), Dec. 2020.

A. Fusova, S. Konev, L. F. Velásquez-García, Z. Sun, E. Nikolaev, “Study on the Thermal Expansion Effects of the 3D Printed Space Instrument”, *Technical digest 15th International Manufacturing Science and Technology Conference*, Sep. 3, 2020; MSEC2020-8293.

A. P. Taylor, J. Izquierdo Reyes, and L. F. Velásquez-García, “Compact, Magnetically Actuated, Additively Manufactured Pumps for Liquids and Gases,” *Journal of Physics D – Applied Physics*, vol. 53, no. 35, 355002 (13pp) Aug. 2020.

Y. Kornbluth, L. F. Velásquez-García, I. Ehrenberg, D. Carter, and K. J. Russell, “Atmospheric Microplasma-Sputtered Micro and Nanowires for Advanced THz Interconnects,” *technical digest 33rd International Vacuum Nanoelectronics Conference (IVNC 2020)*, July 6-10, 2020.