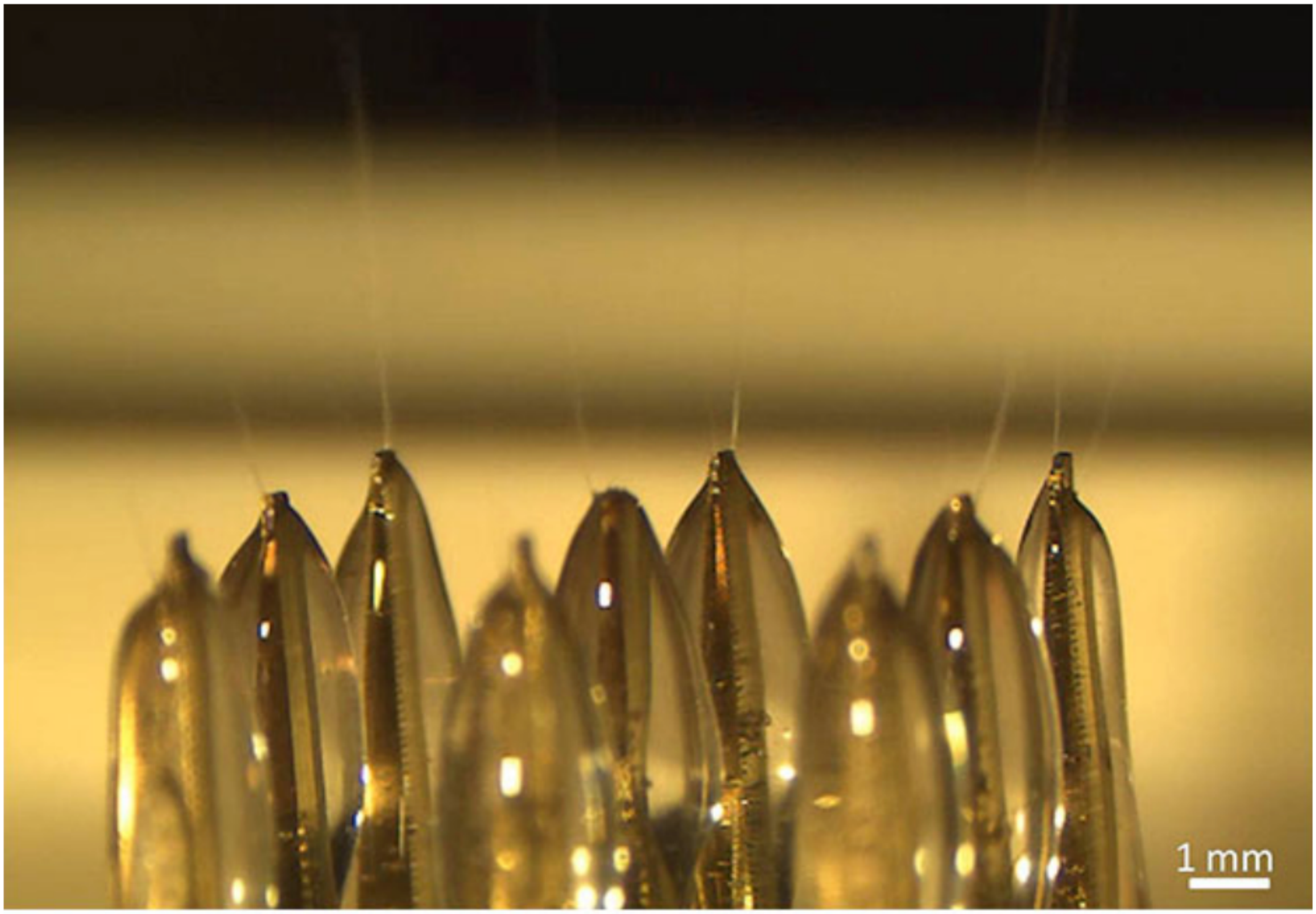


MTL ANNUAL RESEARCH REPORT 2013

Microsystems Technology Laboratories
Massachusetts Institute of Technology
60 Vassar Street, 39-321
Cambridge, MA 02139

Batch-Microfabricated RPA for Ion Energy Measurements

Authors: E. V. Heubel, A. I. Akinwande, L. F. Velásquez-García
Sponsorship: DARPA

Plasma diagnostic tools are required in numerous fields, from experimental physics to aerospace and beyond. Various sensors exist to capture plasma saturation current and plasma potential, and will infer other properties through theory. The retarding potential analyzer (RPA) is device that will directly measure ion energy, a property of interest monitoring exterior craft conditions at hypersonic speeds. Through microfabrication, our device expands the present state-of-the-art to achieve improved mechanically enforced grid alignment, while maintaining the required micron-scale features.

Advantages of enforcing alignment across successive RPA electrodes was already demonstrated in a hybrid device yielding a threefold increase in signal amplitude[1]. In utilizing microelectromechanical system (MEMS) batch-fabrication techniques, alignment precision is refined to the order of 1µm[2]. This MEMS RPA exemplifies the same modularity as the hybrid device, such that grids may be interchanged within the same housing, and otherwise incompatible fabrication techniques might be used. Figure 1 shows the schematic of a complete sensor and the corresponding six-wafer housing stack. Alignment in the assembled device is enforced by curved silicon springs in the housing (Figure 2) which allow for a slight mismatch in nominal and actual grid and housing dimensions, and can accommodate changing dimensions due to thermal expansion. Another advantage of microfabrication is the batch-processing of devices in an effort to drive down costs. MEMS RPA housings are manufactured 30 devices at a time.

Measurements with our MEMS RPA have shown an additional jump in peak signal strength resulting in an order of magnitude increase over its conventional counterpart[3]. In using thicker silicon electrodes over mesh grids, the device is expected to be more robust when exposed to harsher environments. Finally, if batch-fabrication can lead to a more widely available ion energy sensor, this device could find application in monitoring micromachining processes in-situ.

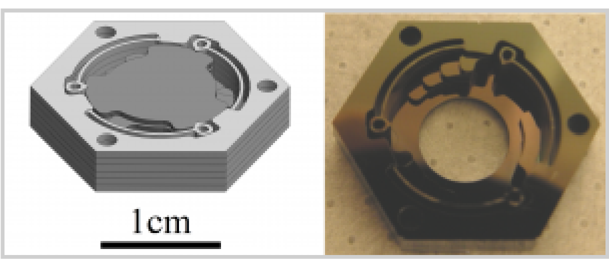


Figure 1: MEMS RPA schematic consisting of housing and grids (left), completed RPA housing (right)[4]

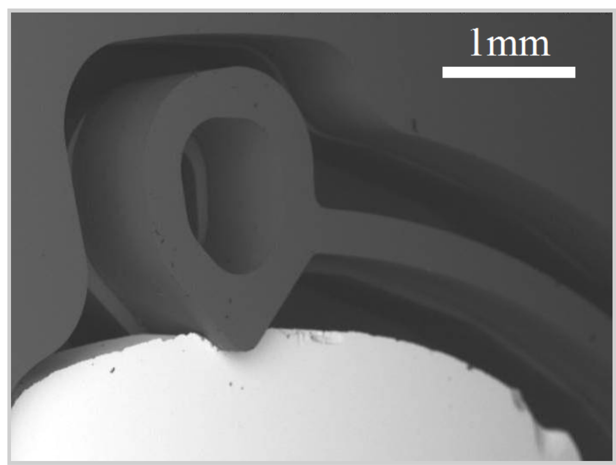


Figure 2: MEMS RPA housing spring clamping a grid into alignment[4]

1. E. V. Heubel, A. I. Akinwande, and L. F. Velásquez-García, "MEMS-Enabled Retarding Potential Analyzers for Hypersonic In-Flight Plasma Diagnostics," *Technical Digest of the 2012 Hilton Head Workshop on Physical Sensors*, Hilton Head, SC, pp. 324 – 327, 2012. [↩]
2. B. Gassend, L. F. Velásquez-García, and A. I. Akinwande, "Precision in-plane hand assembly of bulk-microfabricated components for high-voltage MEMS arrays applications," *Journal of Microelectromechanical Systems*, vol. 18, no. 2, pp. 332-346, Apr., 2009. [↩]
3. E. V. Heubel and L. F. Velásquez-García, "Batch-Fabricated MEMS Retarding Potential Analyzer for High-Accuracy Ion Energy Measurements," *Technical Digest of the 26th IEEE International Conference on Micro Electro Mechanical Systems*, Taipei, Taiwan, pp. 661 – 664, 2012. [↩]
4. E. V. Heubel and L. F. Velásquez-García, "Batch-Fabricated MEMS Retarding Potential Analyzer for High-Accuracy Ion Energy Measurements," Technical Digest of the 26th IEEE International Conference on Micro Electro Mechanical Systems, Taipei, Taiwan, pp. 661 – 664, 2012. [↩] [↩]

Cathode for X-ray Generation with Arrays of Individually Addressable Field Emitters Controlled by Vertical Ungated FETs

Authors: F. A. Hill, S. H. Cheng, L. F. Velásquez-García
Sponsorship: DARPA

This work focuses on the design and fabrication of a cathode for a portable X-ray source. The cathode is made of an array of individually addressable electron guns, each containing double-gated field emitters. Compared to thermionic cathodes, field emission arrays operate at lower vacuum and lower temperatures, use less power and are more portable. The electron beam from each gun is extracted by a proximal gate and collimated using a distal gate before it hits an anode in a micron-sized spot that generates Bremsstrahlung X-rays. Each field emitter is fabricated on top of a vertical ungated field-effect transistor (FET) [1][2] that acts as a current source due to the velocity saturation of electrons in silicon when the voltage across the FET is above a saturation voltage. Current source-like behavior provides spatial and temporal uniformity of the output current across the emitter array; it also protects against emitter burnout and current surges. The extractor and focus gates are monolithically integrated with the cathode chip, and they are patterned in orthogonal strips so that each electron gun can be turned on individually. The first step to make the double-gated field emitters with integrated FETs is to fabricate the FETs and characterize their electrical properties. The fabricated chip is shown in Figure 1a. The FETs are 25 µm tall silicon columns that are 500 nm in diameter and etched in 11 by 11 arrays (Figure 1b and c). The gaps around the columns are filled in with TEOS oxide, vias are etched to the tops of the columns, and then aluminum is deposited to make electrical contact to the tops of the columns (Figure 1d). Electrical characterization tests show that the current saturates across the columns and demonstrate that the current scales with the number of FETs in an array (Figure 2).

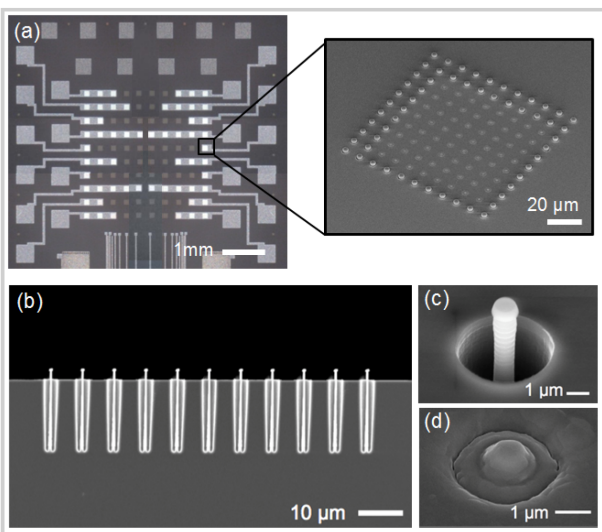


Figure 1: (a) Fabricated cathode chip to characterize the electrical properties of the FETs; (b) scanning electron microscope image of a fabricated array of vertical FETs without dielectric filler; (c) magnified image of the top of a vertical FET without dielectric filler; (d) magnified image of the top of a vertical FET with dielectric filler and deposited metal.

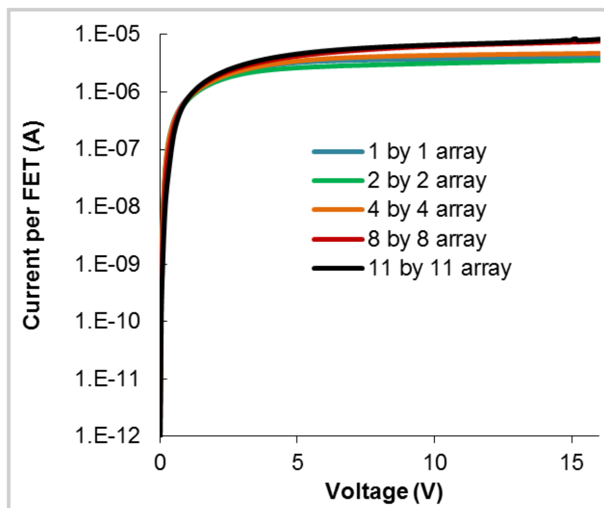


Figure 2: Per-FET current-voltage characteristics showing current saturation and demonstrating that the total current scales with the number of FETs in an array.

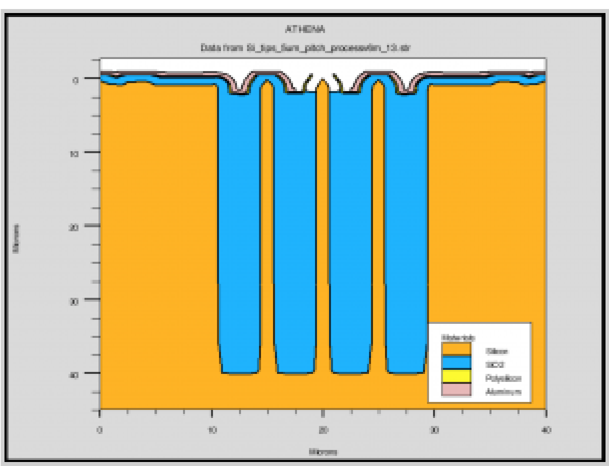
1. L. F. Velásquez-García, S. Guerrera, Y. Niu, and A. I. Akinwande, “Uniform high-current cathodes using massive arrays of Si field emitters individually controlled by vertical Si ungated FETs—Part 1: Device fabrication and characterization,” *IEEE Transactions in Electron Devices*, vol. 58, pp. 1783-1791, June 2011. [↩]
2. L. F. Velásquez-García, S. Guerrera, Y. Niu, and A. I. Akinwande, “Uniform high-current cathodes using massive arrays of Si field emitters individually controlled by vertical Si ungated FETs—Part 2: Device design and simulation,” *IEEE Transactions in Electron Devices*, vol. 58, pp. 1775-1782, June 2011. [↩]

High-Current Cold Cathodes with Temporal and Spatial Emission Uniformity

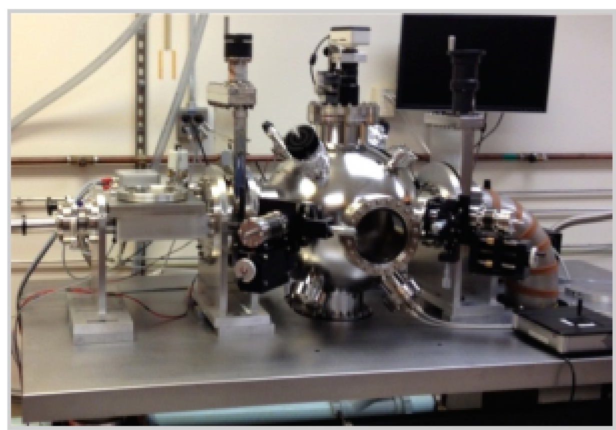
Authors: Michael E. Swanwick, Luis F. Velásquez-García
Sponsorship: DARPA

Field emission arrays (FEAs) are an attractive alternative to mainstream thermionic cathodes, which are power hungry and require high vacuum and high temperature to operate. Field emission of electrons consists of the following two processes: 1) tunneling of electrons through the potential barrier that holds electrons within the material (workfunction φ) when the barrier is deformed by the application of a high electrostatic field[1] and 2) supply of electrons from the bulk of the material to the emitting surface. Either the transmission process or the supply process could be the limiting step that determines the emission current of the field emitter. Control of the transmission process (tunneling) to produce high uniform current from FEAs is very challenging due to the physics of the field emission process. Due to the exponential dependence on the field factor and, hence, the tip radius, emission currents are extremely sensitive to tip radii variation; unfortunately, nanometer-sized tip radii in FEAs have a distribution with long tails that causes severe FEA underutilization. A better approach for achieving uniform emission from nanosharp FEAs is controlling the supply of electrons to the emitting surface. In a metal, the supply of electrons is very high, making the control of the supply challenging. However, in a semiconductor, where the local doping level and the local potential determine the concentration of electrons, it is possible to configure the emitter such that either the supply process determines the emission current.

We are developing high current FEAs where each field emitter is individually ballasted using a vertical ungated field effect transistor (FET) made from a high aspect ratio (40:1) n-type silicon pillar. Each emitter has a proximal extractor gate that is self-aligned for maximum electron transmission to the anode (collector). Our modeling suggests that these cathodes can emit as much as 30 A.cm^{-2} uniformly with no degradation of the emitters due to Joule heating; also, these cathodes can be switched at microsecond-level speeds. The design process flow and mask set have been completed (Figure 1). An ultra-high vacuum chamber has been built to test the devices (Figure 2). The chamber can test full 150mm wafers with four high voltage probes at 10^{-10} torr pressure.



Large array of high aspect ratio pillars with 10nm radius tips with 5 µm hexagonal packing for individually ballasted field emission arrays.



UHV chamber designed and built to conduct electrical characterization of FEAs

1. R. H. Fowler and L. W. Nordheim, "Electron emission in intense electric fields," *Proc. R. Soc. Lond. A*, vol. 119, no. 781, pp. 173–181, May 1928. [↩]

High-throughput Electrospinning of Nanofibers from Batch-microfabricated Arrays

Authors: P. J. Ponce de Leon, F. A. Hill, L. F. Velásquez-Heller
Sponsorship: DARPA

Nanofibers' unique morphological properties promise to make them a key engineering material across many disciplines. In particular, the large specific surface area of the porous webs they form make them highly desirable as multifunctional layers in protective soldier clothing; scaffolds in tissue engineering; and components in devices such as fuel cells, solar cells, and ultra-capacitors[1]. However, their integration into almost all of these technologies is unfeasible as a result of the low throughput and high cost of current production methods. The most common process for producing nanofibers involves applying strong electric fields to polar, high molecular weight polymeric liquids pumped through a syringe in what is known as electrospinning. Electrospinning is the only known technique that can generate nanofibers of arbitrary length and has tremendous versatility as it can create non-woven or aligned mats of polymer, ceramic, semiconducting, and/or metallic fibers.

We implement high-throughput arrays of externally fed, batch-microfabricated electrospinning emitters that are precise, simple, and scalable. We fabricate monolithic, linear emitter arrays that consist of pointed structures etched out of silicon using DRIE and assemble these into a slotted base to form a two-dimensional array. By altering the surface chemistry and roughness of the emitters, we can modify their wetting properties to enable "hemi-wicking"[2] of fluid through the micro-texture (Figure 1). The interplay between electric, surface tension, and viscoelastic forces governs the fluid transport and fiber formation. We achieve more than 30 seconds of continuous, stable electrospinning simultaneously from 9 emitters in a two-dimensional array less than 1 cm^2 using bias voltages under 15kV (Figure 2). This represents a 4-fold increase in run time compared to similar externally fed approaches[3] and a 7-fold increase in emitter density compared to state-of-the-art MEMS electrospinning sources[4]. Future work should explore denser arrays and integration of a proximal extractor electrode.

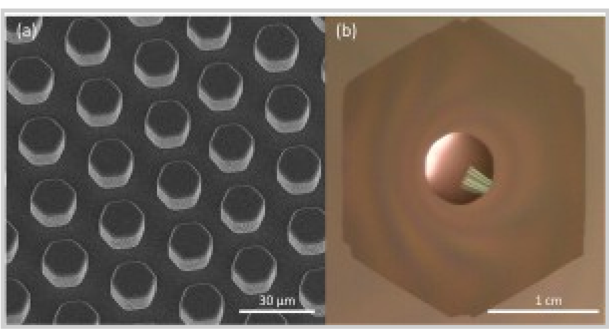


Figure 1: a) Micropillar surface roughness and (b) hemi-wicking spread of a droplet through the roughness.

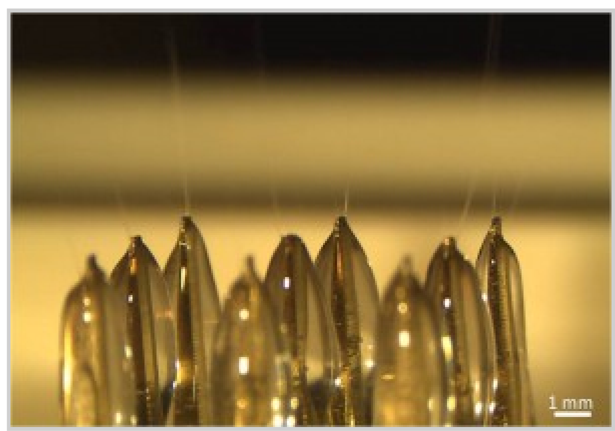


Figure 2: 3×3 array of 5-mm tall emitters producing PEO nanofibers in the stable regime.

1. V. Thavasi, G. Singh, and S. Ramakrishna, "Electrospun nanofibers in energy and environmental applications," *Energy Environ. Sci.,* vol. 1, pp. 205-221, 2008. [↩]
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3. C. Chang, K. Limkrailassiri, and L. Lin, "Continuous near-field electrospinning for large area deposition of orderly nanofiber patterns," *Appl. Phys. Lett.*, vol. 93, 123111, 2008. [↩]
4. Y. Srivastava, M. Marquez and T. Thorsen, "Multi-jet electrospinning of conducting nanofibers from microfluidic manifolds," *J. Appl. Polym. Sci.,* vol. 106, pp. 3171-3178, 2007. [↩]

MEMS-enabled Tactile Displays for the Blind and Visually Impaired

Authors: A. Kani, C. Livermore (NEU), S. Teller, L. F. Velásquez-García, D. Weber, X. Xie (NEU)
Sponsorship: Andrea Bocelli Foundation

According to the World Health Organization, more than 285 million people have visual impairments worldwide, and 39 million of those are blind. About 20% of visual impairments cannot be prevented or cured; in these cases, assistive technologies are critical to enable independent integration into professional and social settings. There is a pressing need for technologies that enable the blind and visually impaired to acquire graphical information or navigate in unstructured environments. The purpose of this project is to enable compact, rapidly refreshable tactile displays that provide information in an intuitive format as part of a broader system for situational awareness, navigation, and perception of graphical information. The overall system is a collaborative effort among MIT's Computer Science and Artificial Intelligence and Microsystems Technology Laboratories, and researchers from Northeastern University; the tactile display is the focus of this abstract.

We are developing the scientific and engineering knowledge for high-resolution displays of rapidly-updatable, vibrating tactile elements, i.e., tactels (Figure 1), using a combination of macro- and microscale batch manufacturing techniques. The proposed architecture is entirely distinct from the conventional piezoelectric bending beams of refreshable Braille readers or the Optacon[1], as well as from the actuators of electroactive polymer displays[2]. Our tactels use structures that receive in-plane displacement from piezo beams to produce amplified out-of-plane displacements that can be sensed by human hands. Current work focuses on parametric multiphysics modeling of the tactels and development of the manufacturing process and assembly approach for the MEMS displays.

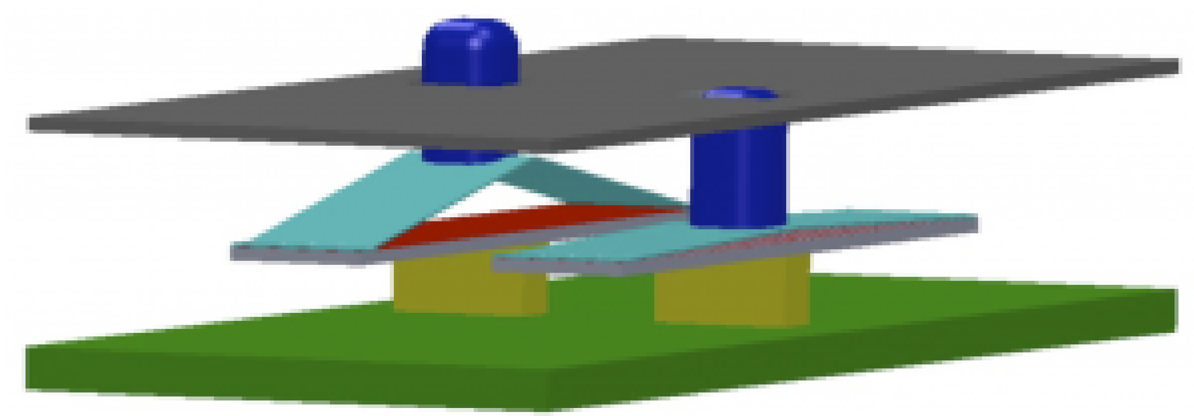

Figure 1: Schematic of two MEMS tactels (one fully actuated and another fully relaxed), showing the piezo actuators (red), displacement amplifiers (light blue), pins (deep blue), and cap plate (gray).

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2. Y. Kato, T. Sekitani, M. Takamiya, M. Doi, K. Asaka, T. Sakurai, and T. Someya, Sheet-type Braille displays by integrating organic field-effect transistors and polymeric actuators*, IEEE Trans. Electron Dev.*, vol 54 , no. 2, pp. 202–209, 2007. [↩]

Microfabricated Ionic Liquid Electrospray Sources with Dense Arrays of Emitters and Carbon Nanotube Flow Control Structures

Authors: F. A. Hill, P. Ponce de Leon, L. F. Velásquez-García
Sponsorship: DARPA

Electrospray is a process to ionize electrically conductive liquids that relies on strong electric fields; charged particles are emitted from sharp tips that serve as field enhancers to increase the electrostatic pressure on the surface of the liquid, overcome the effects of surface tension, and facilitate the localization of emission sites. Ions can be emitted from the liquid surface if the liquid is highly conductive and the emitter flowrate is low. Previous research has demonstrated successful operation of massive arrays of monolithic batch-microfabricated planar electrospray arrays with an integrated extractor electrode using ionic liquids EMI-BF_4 and EMI-Im[1][2] – liquids of great importance for efficient nanosatellite propulsion. The current design builds upon the previous electrospray array designs by increasing the density of the emitter tips, increasing the output current by custom-engineering suitable nanofluidic structures for flow control, and improving the ion optics to gain control of the plume divergence and exit velocity.

The MEMS electrospray source consists of an emitter die and an extractor grid die (Figure 1), both made of silicon and fabricated using deep reactive ion etching. The two dies are held together using a MEMS high-voltage packaging technology based on microfabricated springs that allows precision packaging of the two components with less than 1% beam interception[3][4]. The emitter die contains dense arrays of sharp emitter tips with over 1,900 emitters in 1 cm^2 (Figure 2). A voltage applied between the emitter die and the extractor grid die creates the electric field necessary to ionize the ionic liquid. A carbon nanotube forest grown on the surface of the emitters transports the liquid from the base of the emitters to the emitter tips. The present research focuses on engineering the nanofluidic structure to attain higher emitter current while maintaining good array emission uniformity, and on developing batch microfabricated advanced ion optics for control of the electrospray plume.

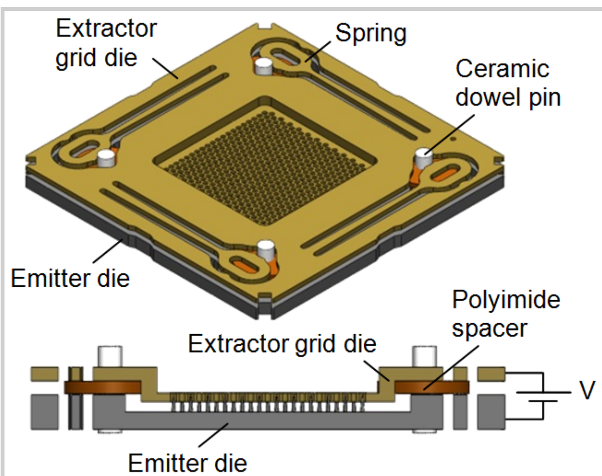

Figure 1: Design of the MEMS electrospray source, consisting of an emitter die containing an array of sharpened emitter tips and an extractor grid die containing a matching array of apertures. When the two dies are assembled, each emitter tip sits centered below an extractor grid aperture.

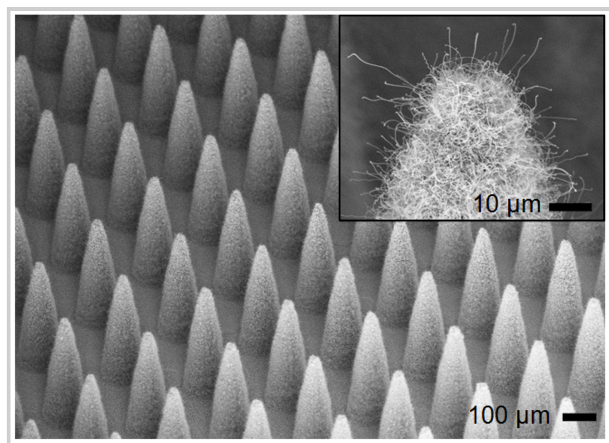

Figure 2: Scanning electron microscope images of an array of microfabricated silicon emitters coated with a carbon nanotube forest.

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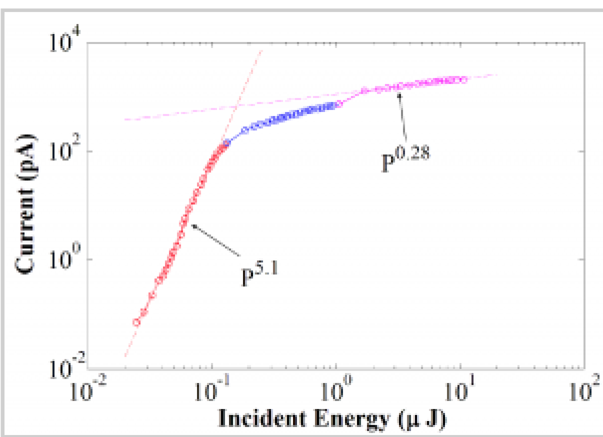
3. B. Gassend, L. F. Velásquez-García, and A. I. Akinwande, “Precision In-Plane Hand Assembly of Bulk-Microfabricated Components for High Voltage MEMS Arrays Applications,” *Journal of Microelectromechanical Systems*, vol. 18, no. 2, pp. 332-326, 2009. [↩]
4. L. F. Velásquez-García, A. I. Akinwande, 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, 2007. [↩]

Next-Generation Ultrafast Photo-Triggered Cathodes

Authors: Michael E. Swanwick, Phillip D. Keathley, Franz X. Kärtner, Luis F. Velásquez-García
Sponsorship: DARPA

State-of-the-art ultrafast cathodes are based on the photoelectric effect, where electrons are emitted from a flat surface using ultraviolet (UV) pulses; however, these cathodes have a number of shortcomings including difficult manufacture, need for ultra-high vacuum to operate, and short lifetime[1]. Photon-triggered field emission cathodes are an attractive alternative to circumvent these issues. Strong-field electron tunneling from solids without damage occurs when the electric field of high-intensity optical pulses interacts with field enhancing structures to lower the incident flux necessary for barrier suppression. In this project we are using wafer-level semiconductor batch fabrication techniques to create massively multiplexed arrays of nano-sharp high-aspect-ratio silicon pillars with high uniformity (4.6-million tips.cm^{-2}), resulting in greatly enhanced array electron emission. A high-aspect-ratio silicon column topped by a nano-sharp tip achieves electron emission at low power by greatly enhancing the incident electric field, and the massive multiplexing of the pillars drastically increases the total current emission. We developed a fabrication process that attains small tip variation across the array due to the diffusion-limited oxidation step that sharpens the tips, resulting in large array utilization. As shown in Fig. 1, the high field of the ultra-short laser pulses combined with the field enhancement of the nano-sharp high-aspect-ratio silicon tip array resulted in large current emission using small laser energies. Between 25 nJ and 0.1 µJ laser pulse energy, the data follow a multi-photon absorption process; the high power dependence of the emitted current on the laser pulse energy comes from the electrons oscillating back into the tip. For larger laser pulse energies the curve bends over, evidencing operation of the cathode in the tunneling regime[2]; this transition occurs because the electric field becomes so strong that the electrons tunnel faster than they can oscillate back into the tips. We have also demonstrated long-term operation without degradation for 3.6 nA average current from an array of about 2,220 tips[3].



Log-log plot of emitted current versus incident laser pulse energy for 10 V anode voltage[4]

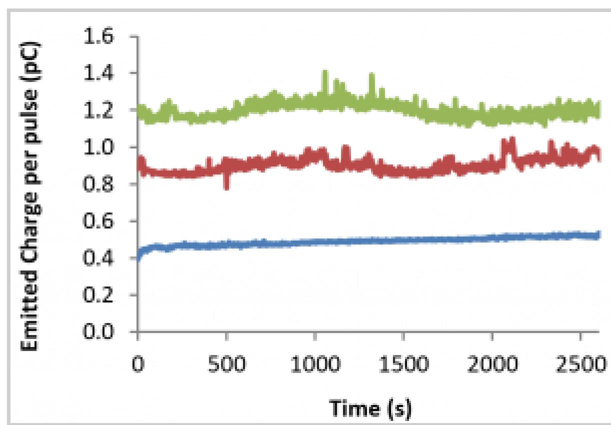


Photo-emitted current versus time. Top green line is 9.5 µJ with 1000 V anode bias, middle red line is 9.5 µJ with 500 V anode bias and the bottom blue line is 3.0 µJ with 500 V anode bias[5]

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2. M. Swanwick, P. D. Keathley, F. X. Kärtner, and L. F. Velásquez-García, "Ultrafast Photo-Triggered Field Emission Cathodes Using Massive, Uniform Arrays Of Nano-Sharp High-Aspect-Ratio Silicon Structures", Technical Digest of the 17th International Conference on Solid-State Sensors, Actuators, and Microsystems, Barcelona, Spain, pp. 2680 – 2683, June 16 – 20 2013. [↩]
3. M. Swanwick, P. D. Keathley, F. X. Kärtner, and L. F. Velásquez-García, "Nanostructured Silicon Photo-cathodes for X-ray Generation", *Technical Digest of the 26th International Vacuum Nanoelectronics Conference*, Roanoke VA, July 8 – 12 2013. [↩]
4. [M. Swanwick, P. D. Keathley, F. X. Kärtner, and L. F. Velásquez-García, "Ultrafast Photo-Triggered Field Emission Cathodes Using Massive, Uniform Arrays Of Nano-Sharp High-Aspect-Ratio Silicon Structures", Technical Digest of the 17th International Conference on Solid-State Sensors, Actuators, and Microsystems, Barcelona, Spain, pp. 2680 – 2683, June 16 – 20 2013. [↩]
5. M. Swanwick, P. D. Keathley, F. X. Kärtner, and L. F. Velásquez-García, "Nanostructured Silicon Photo-cathodes for X-ray Generation", Technical Digest of the 26th International Vacuum Nanoelectronics Conference, Roanoke VA, July 8 – 12 2013. [↩]

Self-aligned Gated Tip Arrays for Low-voltage, High-pressure Field Ionization of Gases

Authors: A. A. Fomani, A. I. Akinwande, L. F. Velásquez-García
Sponsorship: DARPA

Field ion sources operate based on field ionization (FI) phenomena in which an electron tunnels out of a molecule under the influence of a high electric field that lowers and narrows the potential barrier (see Figure 1a). Excellent characteristics in terms of low power consumption, soft-ionization capability, and possibility to operate at high pressures render these devices very attractive for portable analytical instruments. Most commonly, field ionizers are used in field ion mass spectrometers[1] and gas chromatography field ion mass spectrometry systems[2] for analysis of organic molecules and petroleum products. Field ionizers are also investigated for application in atom beam microscopes for study of surface physics[3] and neutron generators for oil-well logging[4]. Although promising, application of field ionizers for portable equipment is currently limited by high operating voltages as the state-of-the-art devices require voltages in excess of 500 V to generate ion currents in nA-range needed for most practical applications[5][6][7].

We designed and fabricated massive arrays of resilient, self-aligned gated nanoscale tips that are capable of field ionizing gases at voltages as low as 150 V. Photolithography and oxidation sharpening were employed to produce a self-aligned device configuration and highly uniform gate and tip dimensions. Electric fields higher than 20 V/nm can be generated with tip-to-gate biases below 200 V that are sufficient to field ionize even helium, with the highest ionization potential of any molecule. The proposed gated tips (Figure 1b) have average tip radii < 5 nm and gate apertures of 3 µm. We demonstrated field ionization of nitrogen at pressures as high as 10 Torr with onset fields of 8–10 V/nm and ion currents > 1 nA at 200 V tip-to-gate bias, as shown in Figure 2.

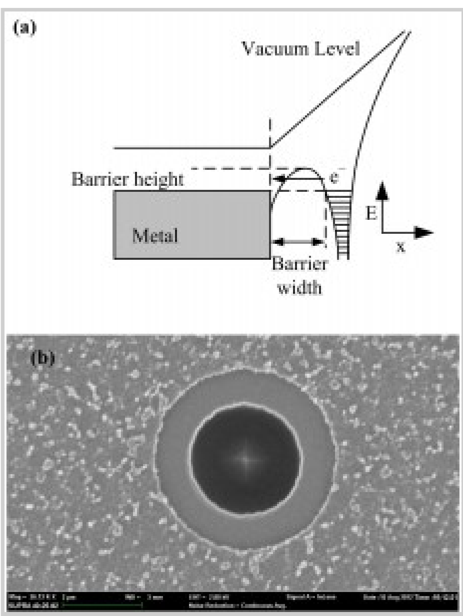

Figure 1: (a) Potential-energy diagram during the field ionization process and (b) SEM image of a self-aligned gated tip.

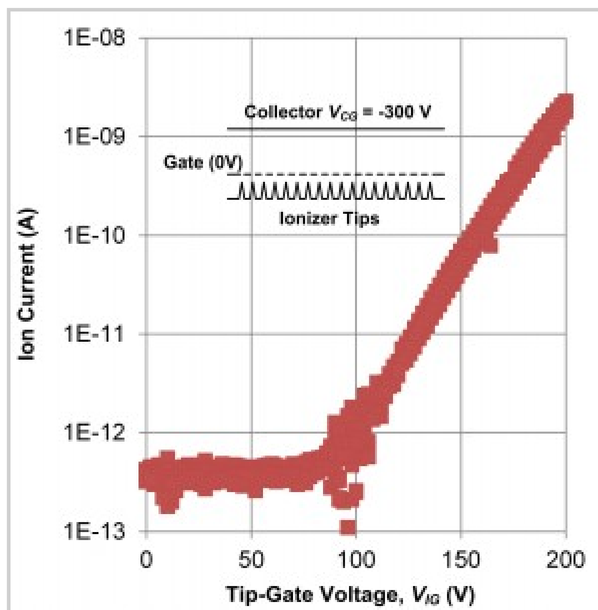

Figure 2: Field ionization of N2: ion current vs. tip-to-gate voltage, VIG, at 10 Torr. Inset shows the experimental setup.

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Silicon Field Emission Devices for X-ray Generation

Authors: S. Cheng, F. A. Hill, L. F. Velásquez-García
Sponsorship: DARPA

This work focuses on developing an X-ray source using microfabricated silicon field emission devices. In the X-ray source, the electrons emitted from a field emission device are accelerated towards a transmission anode plate, generating x-ray (bremsstrahlung) as they decelerate upon reaching surface of the anode plate. Our goal is to fabricate a device with multiple individually addressable emitters to implement coded source imaging technique for phase contrast X-ray imaging[1]. We also need to focus the electron beams generated from each emitter to form a micron-sized interaction spot on the anode. The final device is expected to consist of arrays of silicon tips, with two gates above each of the tips. The proximal gate is for electron extraction, and the distal gate is for electron beam focusing. As a first step of testing the concept, we developed a process flow to fabricate a field emission device with only one gate. The process flow is shown in Figure 1. The fabricated devices can emit 0.2 µA of current per peak, at 75 V of gate-to-emitter extraction voltage. The device will be tested in a home-built X-ray generation facility. The facility, as shown in Figure 2, is a high vacuum (down to 2×10^{-8} Torr) chamber that provides high voltage connections to test X-ray generation functionality of our fabricated field emission devices. The facility accelerates the electrons with up to 60 kV of anode voltage and allows the generated X-ray to transmit out of the chamber through a beryllium window. Initial functionality test of the chamber using a carbon-nanotube field emitter has successfully generated X-ray image of an ex-vivo sample. We expect to generate X-ray image from our first generation silicon field emission devices in the near future.

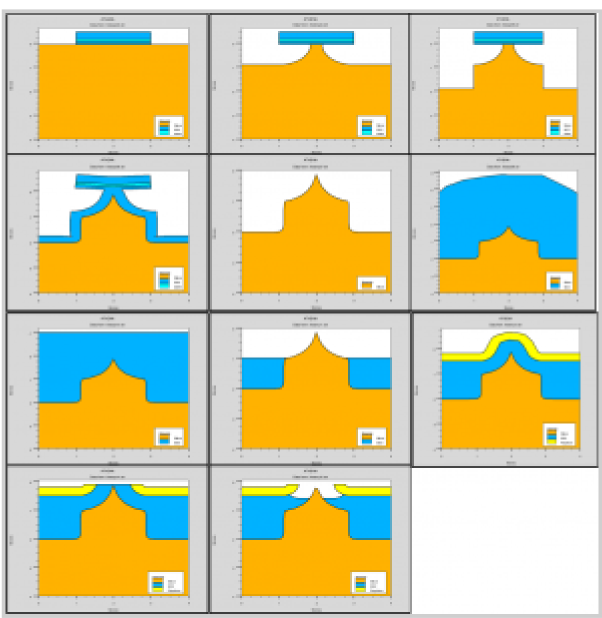

Figure 1: Process flow of the single-gated field emission device, simulated using Silvaco.

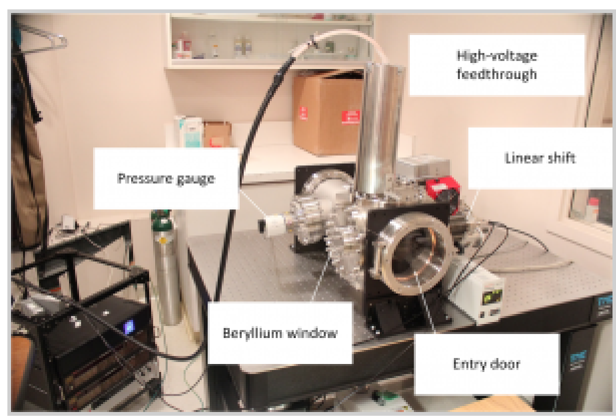

Figure 2: A picture of the X-ray generation facility.

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Luis Fernando Velásquez-García

Principal Research Scientist
Microsystems Technology Laboratories

Collaborators

A.I. Akinwande, EECS, MIT
K. K. Berggren, EECS, MIT
W. Graves, Nuclear, MIT
R. Gupta, Mass General Hospital
B. P. Horn, CSAIL, MIT
F. Kärtner, EECS, MIT
R. Lanza, Nuclear, MIT
C. Livermore, MechE, NU
P. Marek, US Army NSRDEC
M.A. Schmidt, EECS, MIT
K. Senecal, US Army NSRDEC
S. Teller, CSAIL, MIT

Graduate Students

E. V. Heubel, Research Assistant, MechE
V. Jayanti, Research Assistant, EECS
V. Knudsen, Sloan
D. Jeng, Research Assistant, EECS
P. Ponce de Leon, Research Assistant, MechE

Postdoctoral Associates

S. Cheng
A. Fomani
F. Hill
M. Swanwick

Undergraduate Students

M. R. Overlin, EECS, MIT
D. J. Webber, EECS, MIT

Support Staff

C. Collins, Administrative Assistant II

Publications

M. Swanwick, P. D. Keathley, F. X. Kärtner, and L. F. Velásquez-García, "Nanostructured Silicon Photo-cathodes for X-ray Generation", *Technical Digest* of the *26th International Vacuum Nanoelectronics Conference*, Roanoke VA, July 8 – 12 2013.

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