MASSACHUSETTS INSTITUTE
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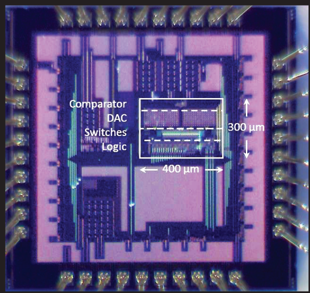
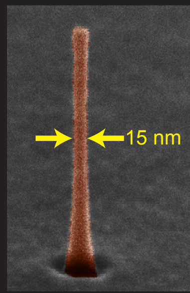
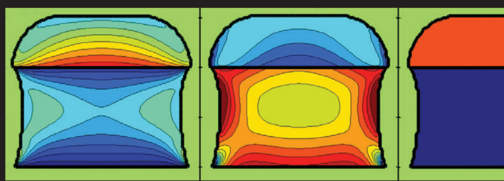
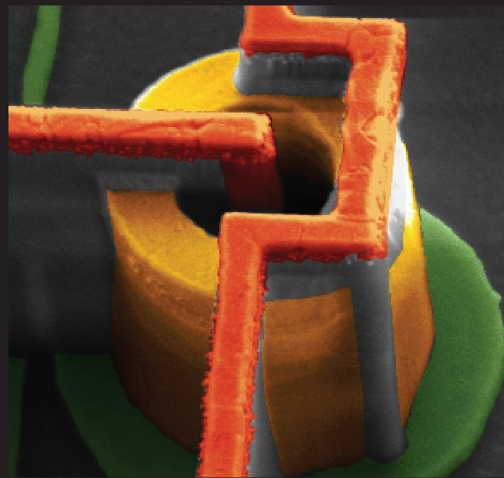
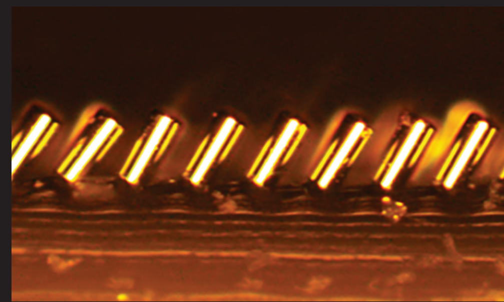
AUGUST 2014



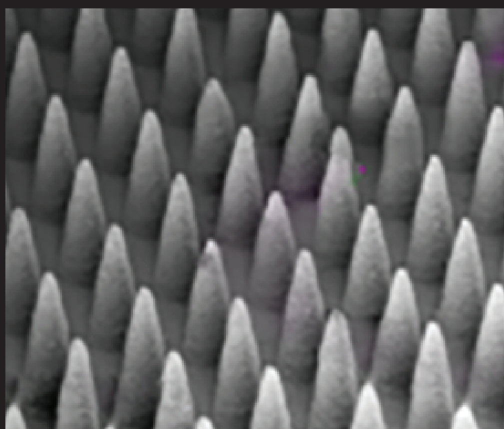



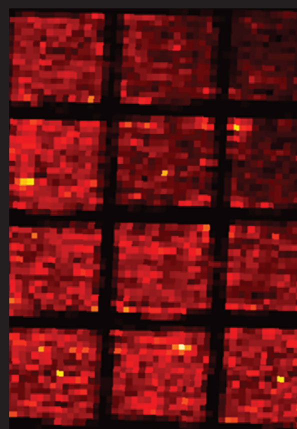


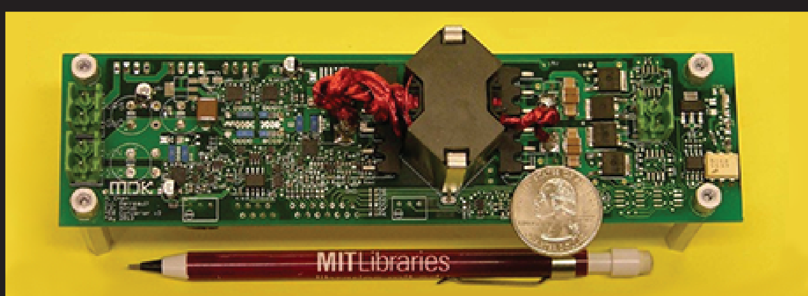


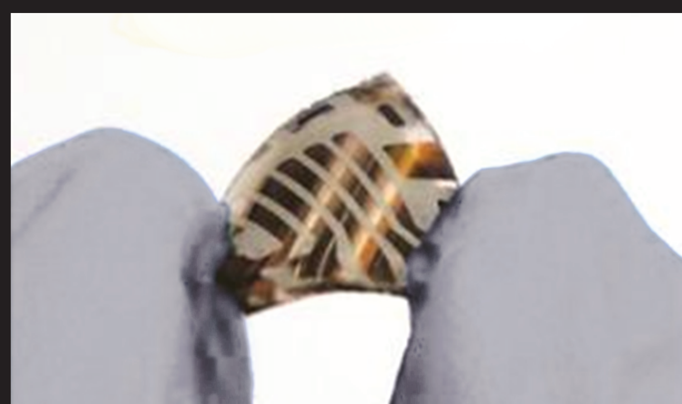
# MICROSYSTEMS TECHNOLOGY LABORATORIES

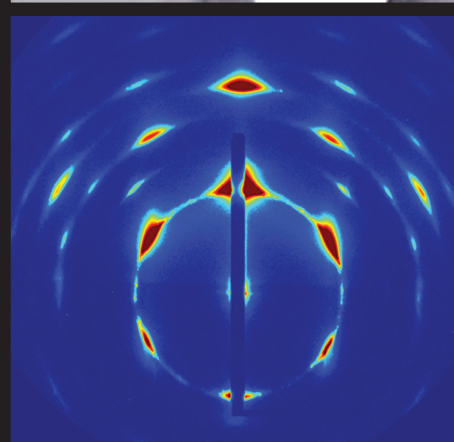
# ANNUAL RESEARCH REPORT 2014

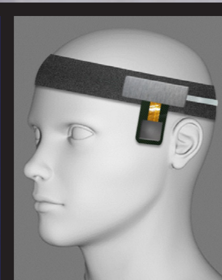










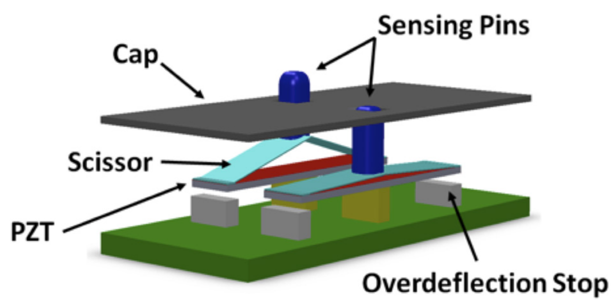
# MEMS Tactile Displays

C. Livermore (NEU), S. Teller, L.F. Velásquez-García, X. Xie (NEU), Y. Zaitsev (NEU)
Sponsorship: Andrea Bocelli Foundation

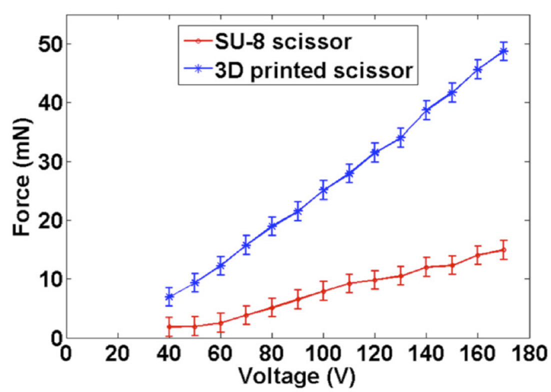
Providing information to people who are blind or have low vision is critical for enhancing their mobility and situational awareness. Although refreshable 2D graphical interfaces are preferred, it is challenging to create actuators that are compact enough to be arrayed into an unlimited number of rows and columns while still being robust, easy to sense, and rapidly switchable. Electroactive polymer actuators are small enough to be arrayed with a few- millimeter pitch and to provide quasistatic millimeter-scale actuations, but they typically have actuation times on the order of seconds. An alternative integrates piezoelectric bending beam actuators perpendicular to the tactile sensing plane, enabling large bending beam actuators to be tightly packed for fully 2D displays.

Ideally, the display's resolution should be about one tactel (i.e., tactile element) per $mm^2$, which is the density of mechanoreceptors in human finger pads. It should be refreshable in real time (hundreds of Hz, i.e., the frequency response of human touch), allowing the contents of the display to keep up with rapidly changing inputs. Since humans are much more sensitive to motions and changing stimuli than to static patterns, the display should code information not only as static patterns, but also as simulated motion against the user's finger pads. Finally, the power consumption of the display should be compatible with portable use. Although existing displays meet various subsets of these requirements, no existing display can meet all requirements simultaneously.

We are developing tactile displays based on a new type of MEMS tactile actuator created to target these requirements. This new actuator concept uses an extensional piezoelectric actuator that operates a scissor amplifier that transforms the in-plane movement of the piezo into amplified out-of-plane movement (see Figure 1). We have shown these tactile elements to be effective at the milliscale. Their measured performance agrees with the models, with maximum deflections of greater than 10 μm and maximum forces above 45 mN (as in Figure 2) that place the devices well above the sensing threshold. Our analytical model based on ideal pinned hinges is shown to be useful for predicting the behavior of tactels with flexural hinges, especially when coupled with FEA to predict hinge failure. The analytical model validation provides support for further downscaling of the tactile elements to achieve 100 tactels/$cm^2$. The measured performance confirms sensing thresholds of less than 4 μm and 2 mN for the most effective tactile devices.




▲ Figure 1: Schematic diagram of piezoelectric extension actuators (red) topped by scissor amplifiers (light blue) and cap plate.




▲ Figure 2: Measured tactel force vs. peak amplitude of the applied voltage. Markers represent data; lines guide the eye.

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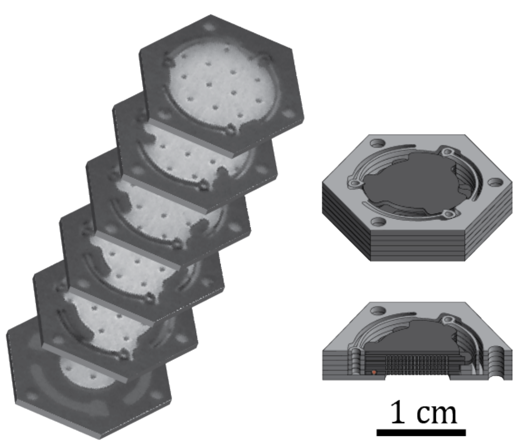
# Ion Energy Measurements of Dense Plasmas with a Microfabricated RPA

E.V. Heubel, L.F. Velásquez-García
Sponsorship: NASA

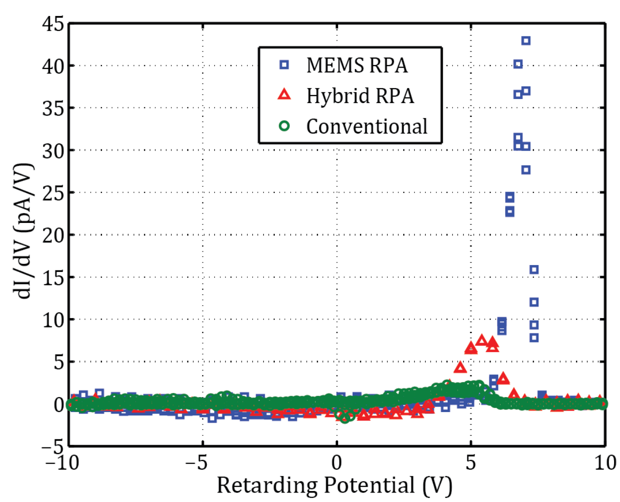
The energy of ions determines the efficiency of plasma propulsion systems and governs surface chemical reactions in plasma etching chambers. In plasma diagnostics, the instrument used to measure the ion energy distribution is the Retarding Potential Analyzer (RPA). However, high-density plasmas of interest require tens- to hundreds-of-microns scale dimensions. Through MEMS processing techniques, our RPA achieves the small aperture sizes necessary to measure dense plasmas. Precise alignment between successive microfabricated grids is achieved through compliant support structures in the housing (as Figure 1 shows). The silicon spring tips mate with corresponding notches in the electrodes to provide robust alignment on the order of 1 µm and to increase the overall sensor's ion transmission.

Our previously reported RPA, deemed "hybrid" on account of incorporating microfabricated electrodes in a conventionally machined sensor, demonstrated improved performance over conventional RPAs. By reducing the aperture size while enforcing some degree of aperture alignment, we achieved a better resolution with no loss in signal strength compared to conventional mesh RPAs. Measurements of the ion energy distribution in a helicon plasma were obtained at MIT's Plasma Science and Fusion Center using our sensors with microfabricated electrodes having 100 µm apertures. However, as a consequence of its larger apertures, the conventional RPA design was unable to effectively trap the plasma, and therefore no ion distribution could be extracted with this traditional device.

Figure 2 shows ion energy distributions obtained with an ion source comparing the performance of a conventional RPA (with 152 µm apertures), the hybrid RPA (with 100 µm apertures), and MEMS RPA (with 150 µm apertures). The MEMS RPA design utilizes a fully microfabricated housing to improve upon the inter-grid aperture alignment over the hybrid sensor. Additionally, various aperture diameters are utilized in the electrode stack to mitigate current interception within the sensor. These RPA improvements result in an order of magnitude increase in signal strength over the conventional device and a threefold increase in energy distribution resolution.




▲ Figure 1: MEMS RPA housing exploded view (left) of actual wafer layers. Concept and cross-section view of sensor with assembled electrodes (right).




▲ Figure 2: Ion energy distribution measurements of a mass spectrometry ion source. The MEMS RPA shows an order-of-magnitude increase in signal strength compared to a conventional RPA with similar aperture sizes, accompanied with a threefold reduction in peak width associated with increased sensor resolution.

## FURTHER READING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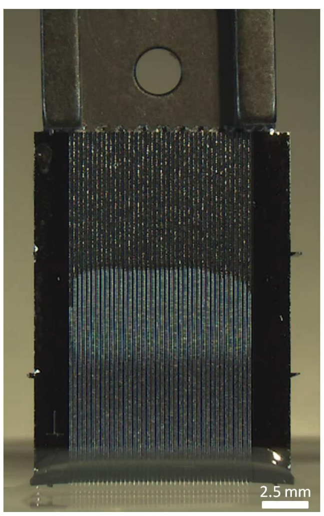
# High Throughput Electrospinning of Nanofibers from Batch-microfabricated, Externally-fed Emitter Arrays

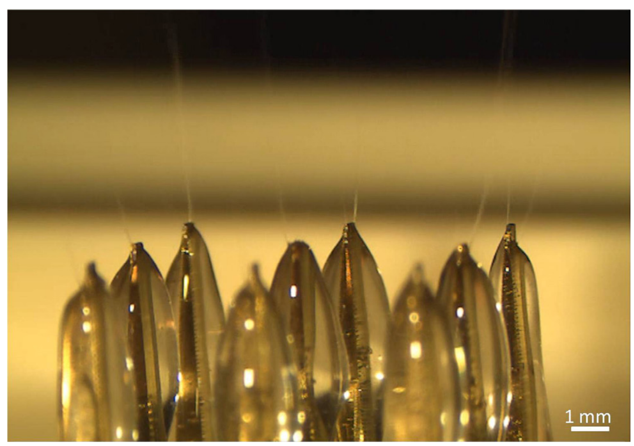
P.J. Ponce de Leon, F.A. Hill, L.F. Velásquez-García

Nanofibers promise to be a key engineering material in the near future due to their unique, nanoscale morphological properties. In particular, the large specific surface area of the porous webs they form make them highly desirable as scaffolds for tissue engineering; layers in multifunctional filters/membranes; and components in devices such as fuel cells, solar cells, and ultra-capacitors. However, their integration into almost all of these technologies is unfeasible as a result of the low throughput, high cost, and poor control 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; it 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 wicking of fluid through the micro-texture (as in Figure 1). The interplay between electric, viscoelastic, and surface tension forces governs the fluid transport and fiber formation. We achieve over 30 seconds of stable electrospinning of polyethylene oxide (2-4% w/v in 60/40 water/ethanol solution) from 9 emitters in a two-dimensional array with a density of 11 emitters/cm$^2$ using bias voltages around 10kV (see Figure 2). This density is 7 times greater than the emitter density achieved in similar array-based approaches. Current work focuses on characterization of larger, denser arrays to demonstrate uniform emission.




▲ Figure 1: Capillary rise against gravity of a 2% w/v polyethylene oxide (PEO) solution through microtrenches. Sufficient liquid supply is necessary for continuous electrospinning.




▲ Figure 2: Stable production of PEO nanofibers from a 3×3 array of 6-mm tall micropillar-patterned emitters.

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- C. Chang, K. Limkrailassiri, and L. Lin, “Continuous near-field electrospinning for large area deposition of orderly nanofiber patterns,” *Appl. Phys. Lett.*, vol. 93, p. 123111, 2008.
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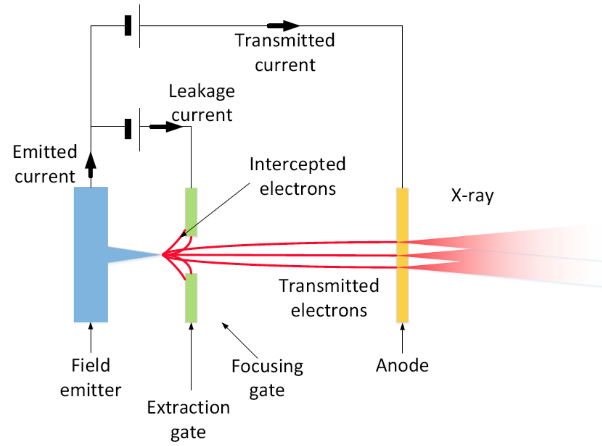
# Near-Monochromatic X-ray Sources Using a Nanostructured Field Emission Cathode and a Transmission Anode for Markerless Soft Tissue Imaging

S. Cheng, F.A. Hill, E.V. Heubel, R. Gupta (MGH), L.F. Velásquez-García
Sponsorship: DARPA

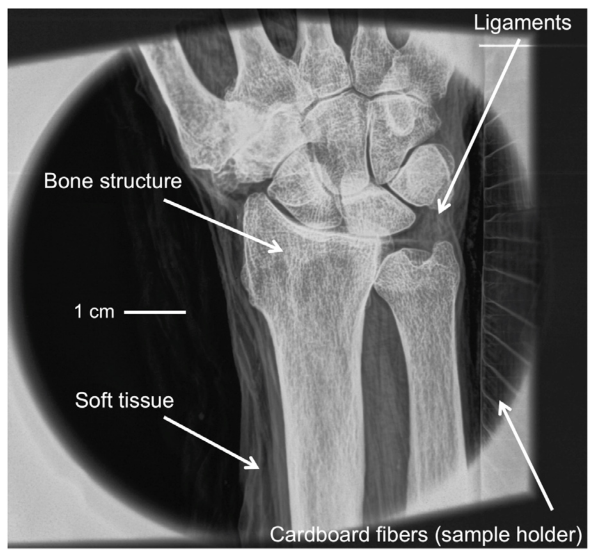
A conventional X-ray generator consists of a thermionic cathode and a reflection anode inside of a vacuum chamber that has an X-ray transmission window. The cathode generates a beam of electrons that is accelerated towards the anode, which is biased at tens of kilovolts above the cathode voltage. Some of the electrons collide with the anode and convert their kinetic energy into radiation, a fraction of which escapes the vacuum chamber through a transmission window made of a suitable material, such as beryllium. The X-ray emission is a mix of bremsstrahlung radiation (broad, continuous spectrum) and fluorescence (emission at specific peaks corresponding to atomic shell transitions). Conventional X-ray technology requires high vacuum to operate, does not efficiently produce X-rays, and has overall low power efficiency. Conventional X-ray generators cannot image well soft tissue unless contrast media, i.e., markers, are employed.

We are developing efficient X-ray generators capable of soft tissue imaging using batch-microfabricated field emission cathodes composed of arrays of self-aligned, gated, and nanometer-sharp n-silicon tips, and a microstructured transmission anode (Figure 1). The nanostructured silicon cathode operates at low voltage and reliably achieves high-current emission with high transmission. The transmission anode efficiently generates X-rays while reducing the background radiation, resulting in emission of X-rays with narrow spectral linewidth for sharp imaging of biological tissue.

Using our first-generation X-ray source (a tabletop apparatus), we have obtained absorption images of ex-vivo samples that clearly show soft tissue and fine bone structures (Figure 2). Current work focuses in miniaturizing the X-ray source into a portable system, and in improving the cathode and anode components to achieve generation of coherent X-rays to make possible phase contrast imaging at a low cost.




▲ Figure 1: Schematic of an X-ray generator with a field emission cathode and a transmission anode.




▲ Figure 2: Absorption X-ray image of an ex-vivo human wrist showing soft tissue structures and fine details of the bone structure.

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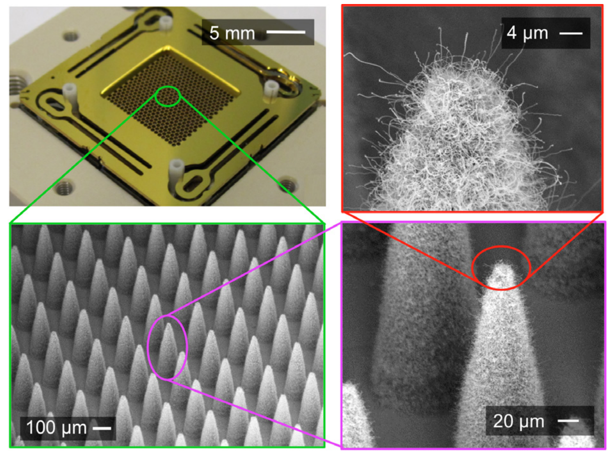
# Multiplexed MEMS Electrospray Emitter Arrays with Integrated Extractor Grid and CNT Flow Control Structures for High-Throughput Generation of Ions

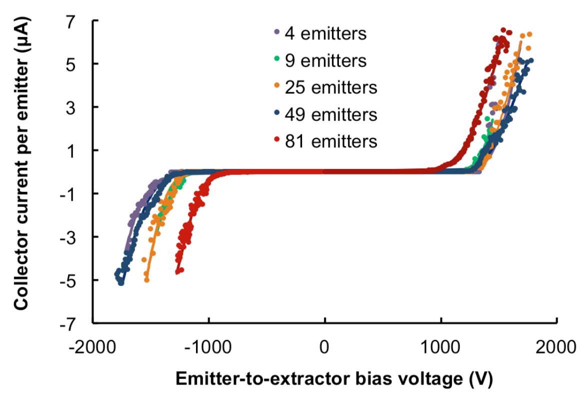
F.A. Hill, E.V. Heubel, P. Ponce de Leon, L.F. Velásquez-García
Sponsorship: DARPA

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—liquids of great importance for efficient nanosatellite propulsion and nanomanufacturing. The current design builds upon a previous electrospray array designs from our group by increasing the area density of the emitter tips and increasing the output current by custom-engineering nanofluidic structures for flow control.

Our MEMS multiplexed 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 low beam interception. The emitter die contains dense arrays of sharp emitter tips with over 1,900 emitters in 1 cm². 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. Our electrospray arrays operate uniformly (Figure 2), and mass spectrometry of the emission demonstrates that our devices only produce ions.




▲ Figure 1: (in counter-clockwise starting on the upper left corner) array of 2,000 electrospray emitters in 1 $cm^2$ with integrated extractor grid; close-up of electrospray emitter forest; close-up of a single electrospray emitter covered by a layer of CNTs; detail of an emitter tip.




▲ Figure 2: Collector current per emitter as a function of emitter-to-extractor bias voltage for (A) the electrospray sources with 4, 9, 25, 49 and 81 emitters in 1 $cm^2$ evidencing great array uniformity.

## FURTHER READING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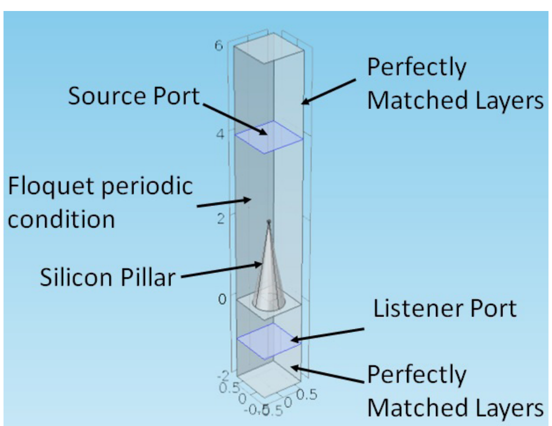
- F. A. Hill, E. V. Heubel, P. Ponce de Leon, and L. F. Velásquez-García, "High-Throughput Ionic Liquid Ion Sources Using Arrays of Microfabricated Electrospray Emitters with Integrated Extractor Grid and Carbon Nanotube Flow Control Structures", *accepted for publication, IEEE/ASME Journal of Microelectromechanical Systems,* DOI 10.1109/JMEMS.2014.2320509.

# Exploration of the Packing Limits of Ultrafast, Optically-triggered Silicon Field-emitter Arrays Using the Finite Element Method

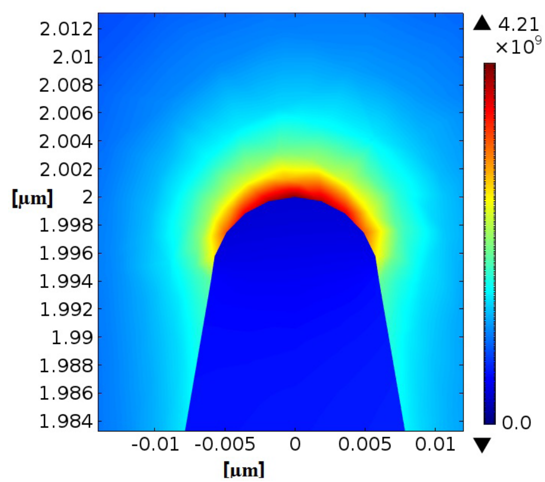
C. Dong, M.E. Swanwick, P.D. Keathley, F.X. Kärtner, L.F. Velásquez-García
Sponsorship: DARPA

Ultrafast optically-triggered field emission cathodes bypass several disadvantages demonstrated by current state-of-the-art ultrafast cathodes, such as requiring ultra-high vacuum to operate and short lifetime, and are a promising technology for implementing spatially-structured electron sources for applications such as free-electron lasers, compact coherent X-ray sources, and attosecond imaging. Ultrafast optically-triggered cathodes composed of massive arrays of high aspect-ratio silicon pillars capped by nano sharp tips and 5 μm pitch were fabricated at MIT MTL. The effect of the geometry and the morphology of the Si pillar arrays on the ultra-fast emission characteristics of such cathodes is now explored using the finite element modeling in 2D and 3D.

Since the field-emitted current depends exponentially on the surface electric field, we are interested in studying how the electric field is enhanced by the geometry and the morphology of the Si pillar arrays. We selected COMSOL Multiphysics to simulate the electric field of the devices. The 3D model (see Figure 1) consists of a single tapered pillar 2.0 μm tall and 0.7 μm wide at the base with a 6-nm radius hemispherical cap. Perfectly matched layers (PMLs) are added on the top and bottom to absorb the excited and higher order modes. Floquet periodicity is applied on the four sides of the unit cell to simulate the infinite 2D array. The port boundary condition is applied on the interior boundary of the PML as the excitation port to simulate the 800-nm incident wave at a glancing angle of 84° from normal (the same experimental setup described in the third reading below). This model is validated by verifying the Fresnel equations between Si and vacuum before inserting the Si pillar. The 2D slice contour plot (see Figure 2) shows the simulated electric field from a 1 GV/m incident field on an emitter with 1-μm pitch using frequency domain analysis. The maximum electric field at the tip is about 4.2 GV/m, i.e., the emitter tip has an field enhancement factor of ~4.2. Both 2D and 3D models are utilized to explore the effect of the geometry and the morphology of the Si pillar arrays on the field enhancement.




▲ Figure 1: The 3D COMSOL model consists of a single pillar, PMLs on the top and bottom, Floquet periodicity on four sides, and a source port with an incident 800-nm wave at a glancing angle of 84°.




▲ Figure 2: 2D slice contour plot from the 3D model with 1-μm pitch shows the maximum electric field at the tip, with a field enhancement factor of ~4.2.

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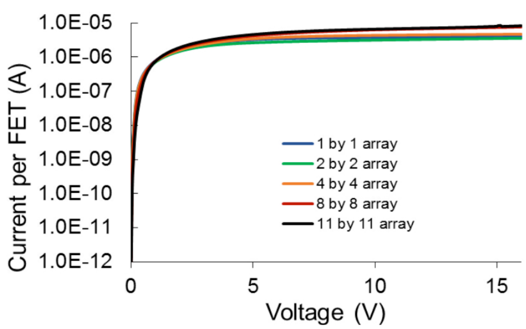
# High-Current Field Emission Cold Cathodes with Temporal and Spatial Emission Uniformity

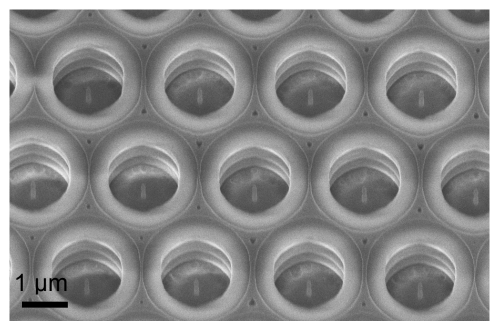
M.E. Swanwick, F.A. Hill, L.F. Velásquez-García
Sponsorship: DARPA

Field emission arrays (FEAs) are an attractive alternative to mainstream thermionic cathodes, which require high vacuum and high temperature to operate. Field emission of electrons consists of the following two processes: first, the transmission of electrons (tunneling) through the potential barrier that holds electrons within the material (workfunction $\phi$) when the barrier is deformed by a high electrostatic field and second, the 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. Due to the exponential dependence on the field factor, the emission current from the tips is extremely sensitive to tip radii variation. We have a process to achieve uniform emission from nanosharp FEAs by both fabricating highly uniform tip arrays and controlling the supply of electrons to the emitting surface (see Figure 1).

We have designed and fabricated FEAs in which 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, mask set, and pillar arrays have been completed (as Figure 2 shows) with the self-aligned extractor gate. An ultra-high vacuum chamber has been built to test the devices. The chamber can test full 150mm wafers with six high voltage feed through and a step-down anode at $2x10^{-10}$ torr pressure while also imaging the electron emission on a phosphorus screen.




▲Figure 1: IV curves for high aspect ratio Si (1-2 Ω.cm) pillars showing current saturation for 1, 4, 16, 64, and 121 pillars. Each pillar is 25 µm tall, 500 nm in diameter, and capped with Al for ohmic contact.




▲Figure 2: SEM image of a large array of high aspect ratio pillars with 10-nm radius tips with 5-µm hexagonal packing for individually ballasted field emission with self-aligned gates.

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# Photoactuated Ultrafast Silicon Nanostructured Electron Sources for Coherent X-ray Generation

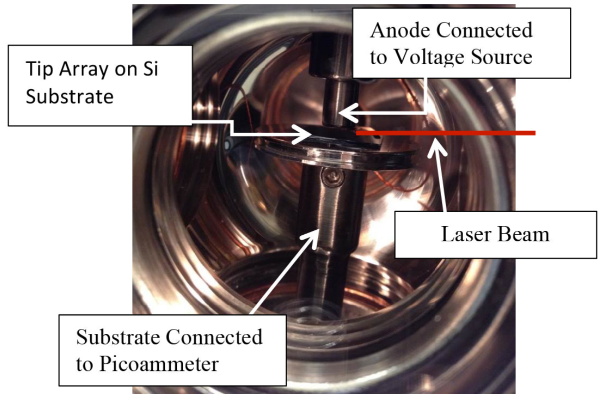
M.E. Swanwick, P.D. Keathley, C.D. Dong, F.X. Kärtner, L.F. Velásquez-García

Sponsorship: DARPA

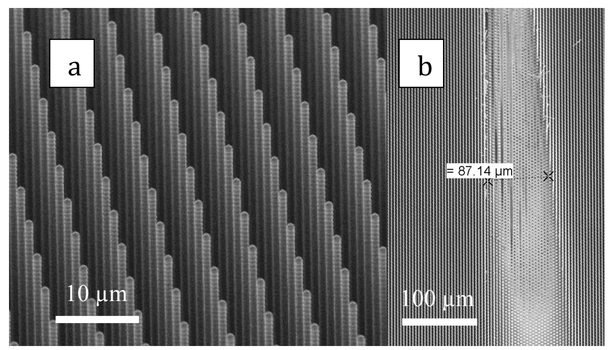
Nanostructured cathodes that can be switched at an ultrafast time scale (<50 ps) have applications in free-electron lasers and coherent X-ray sources. This project is creating the theory, modeling, and experimental results for a compact coherent xray source for phase contrast medical imaging based on inverse Compton scattering of relativistic electron bunches. The X-ray system requires a low-emittance electron source that can be switched at timescales in the low femtosecond range.

The focus of our work has been the design, fabrication, and characterization of massive arrays of a nanostructured high aspect-ratio silicon structures to implement low-emittance and high-brightness cathodes that are triggered using ultrafast laser pulses to produce spatially uniform electron bunches. Laser pulses at 35 fs, 800 nm and a 3 kHz repetition rate from a titanium sapphire laser at an 84° glancing angle, inside a vacuum chamber at ~$10^{-8}$ torr bathe a highly uniform array of ~2200 silicon pillars with a 5-µm pitch. The cathode chip is connected to ground through a picoammeter while the anode, a 0.25-inch plate 3mm above the cathode, connects to a voltage supply (see Figure 1). The cathodes show stable emission and emit over 1.2 pC average charge for over 8-million pulses when excited with 9.5-µJ laser energy with no degradation of the emission characteristic of the cathode. This result shows that silicon-based photon-triggered cathodes processed with standard CMOS processes and operated at high vacuum can function for extended periods without performance degradation.

The cathodes are fabricated from single-crystal <100> n-Si 1-10 Ω-cm wafers. The result is massive arrays of pillars (over half a million elements with 5-µm hexagonal packing) capped by tips with under-5-nm average tip radius and less than 1-nm standard deviation (see Figure 2). Through simulation and experiment we have demonstrated that the emitters operate in two distinctive regimens, i.e., the low-electric field multi-photon regime (similar to a typical photocathode), and the high-field quantum tunneling regime (similar to a field emission cathode). Actuation of the devices with laser pulses of 10 µJ or lower results in electron emission with no device degradation.




▲Figure 1: Experimental set-up with an 800-nm 35-fs laser beam with 80-µm spot size hitting the cathode at 84°.




▲Figure 2: (a) SEM of high aspect-ratio single-crystal Si pillars with uniform nanosharp tips. (b) Damage to Si tips after exposed to 20.5-µJ laser pulses.

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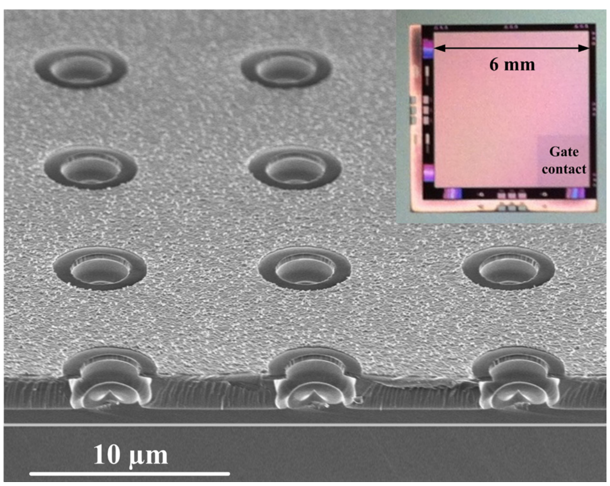
# Field Emission Neutralizers for Electric Propulsion of Small Spacecraft in Low Earth Orbit

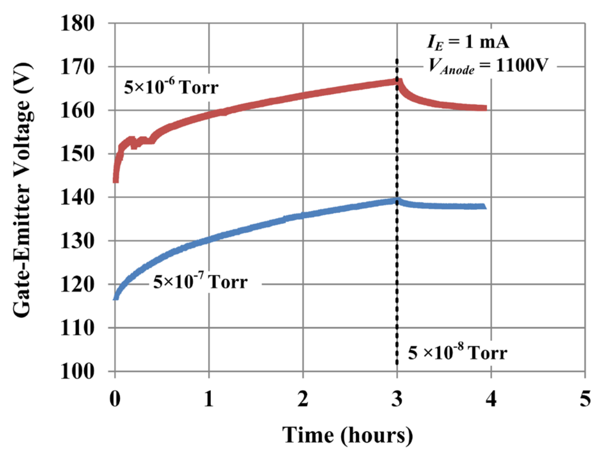
A.A. Fomani, A.I. Akinwande, L.F. Velásquez-García
Sponsorship: DARPA

Electric propulsion (EP) systems are excellent candidates for small spacecraft since EP systems consume less propellant than chemical rockets. In EP systems such as field emission electric propulsion thrusters (FEEPs), ion engines, and hall thrusters, a beam of positive ions is ejected at high speed to produce thrust. If the ejecting charge is not compensated, the operation of the EP system will negatively charge the spacecraft, reducing the propulsion efficiency and eventually stopping the thruster. Hence, development of robust, low-power, and high-current neutralizers that do not consume propellant is necessary to advance the state of the art of EP systems for small spacecraft. Field emission neutralizers (FENs) are promising candidates because of their low power consumption, high specific current, small size, and lack of propellant consumption. For operation in LEO, neutralizers must withstand long-term operation in environments with oxygen partial pressures of ~$5×10^{-7}$ Torr. Carbon nanotube-based FENs could satisfy these requirements; however, they require biases higher than 600 V for 1 mA emission current.

This work develops arrays of Pt-coated, self-aligned, gated tips as low-voltage FENs for electric propulsion of small spacecraft in low Earth orbit. The neutralizers consist of 320,000 tips with 10 μm pitch and 5-10 nm tip radii; they have an integrated self-aligned gate electrode with 3 μm apertures. The devices emit currents higher than 1 mA at bias voltages as low as 120 V, i.e., similar currents at five-fold less bias voltage and emission area than state-of-the-art CNT neutralizers. The devices have a 2.5-μm-thick gate dielectric to prevent device failure due to dielectric breakdown; the tips are coated with a 10-nm-thick Pt film to improve the tip resistance against ion bombardment and reactive gasses. Continuous emission for 3 hours at pressures of $5×10^{-6}$ Torr in air was demonstrated. Less than 60 V increase in the gate-emitter voltage was sufficient to maintain the emission current at 1 mA.




▲ Figure 1: SEM image of Pt-coated self-aligned gated Si tips. The inset shows optical image of a field emitter neutralizer with 0.32 $cm^2$ active area consisting of 320,000 gated nanometer-scale tips.




▲ Figure 2: . Continuous field emission at $5×10^{-6}$ and $5×10^{-7}$ Torr in air. Less than 60 V increase in the gate-emitter voltage was sufficient to maintain the current at 1 mA.

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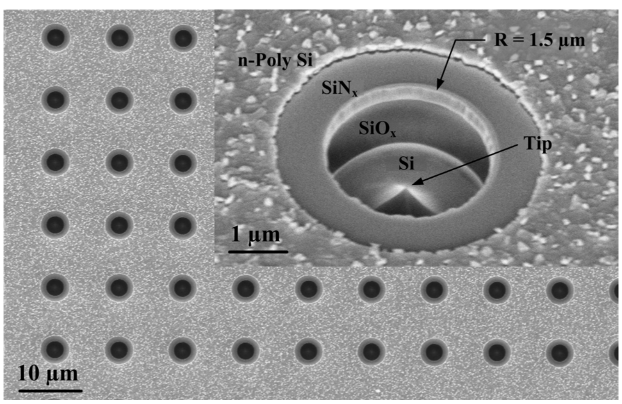
# Low-Voltage High-Pressure Gas Field Ionizers

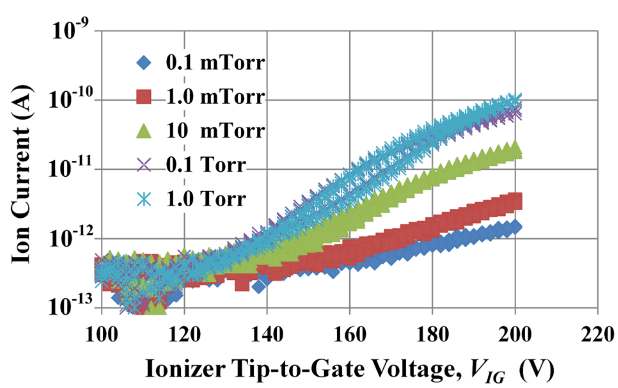
A.A. Fomani, L.F. Velásquez-García, A.I. Akinwande
Sponsorship: DARPA

Low power consumption, soft-ionization capability, and the potential for operation at high pressures are characteristics desired in gas ionizers for application to portable analytical instruments. Unlike impact ionization techniques, field ionization provides an efficient method for producing stable molecular ions—even from complex organic compounds. Consequently, field ion sources can generate nonfragmented ions for exact measurement of the mass-to-charge ratio of an analyte. These devices are used in various analytical instruments such as field ion mass spectrometers (FIMS) and atom beam microscopes. Other applications include gas chromatography FIMS for analysis of petroleum products and neutron generators for detection of shielded nuclear material and oil-well logging. Despite the attractive features offered by field ion sources, long-term, reliable, and high pressure operation has not been reported due to high voltages (> 500 V) needed for field ionization using the current state-of-the-art devices.

We have developed low-voltage Torr-level gas field ionizers with operating voltages as low as 150 V even for He, which has the highest ionization potential among molecules. The ionizer consists of a large array of Pt-coated self-aligned gated Si tips with radii <10 nm and gate apertures of 3 µm. The tips were designed to generate fields above 20 V/nm at gate-to-tip voltages lower than 200 V while the field at the edge of the gate remains below 0.2 V/nm. A 2.5-µm-thick stack of silicon oxide/silicon nitride was employed as the gate dielectric to limit the field intensity inside the gate dielectric to less than 100 V/µm, allowing prolonged operation of the device. Continuous field ionization of He and $N_2$ for $10^4$ s was achieved at pressures as high as 10 Torr. A slow decay in ion current was observed over time, which can be explained by adsorption of particles at the tip surface. Nevertheless, the original device characteristics can be recovered by operating the device as field emitter in a high vacuum (<$10^{-7}$ Torr).




▲ Figure 1: SEM images of the fabricated gated tip arrays employed as gas field ionizers.




▲ Figure 2: Field ionization of helium—ion current vs. tip-to-gate voltage at different pressures.

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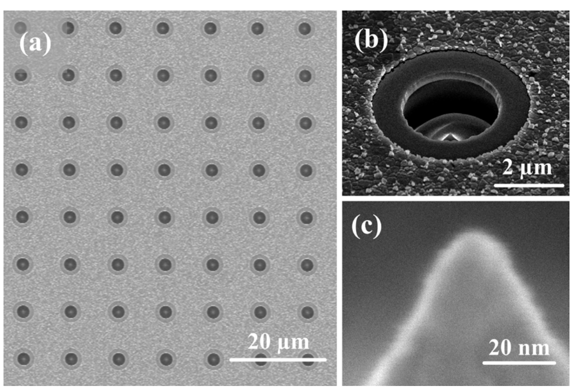
# Large-Area Field Emission Arrays for High-Current Applications

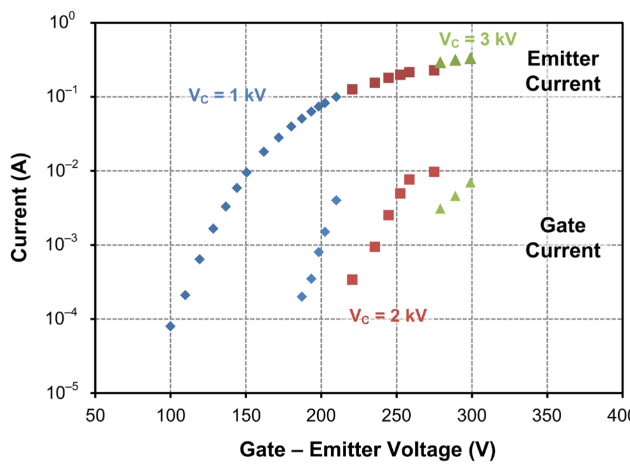
A.A. Fomani, L.F. Velásquez-García, A.I. Akinwande
Sponsorship: DARPA

Gyrotrons, free electron lasers (FELs), and THz vacuum electronic devices require intense high-current electron beams. High-current, high-current-density electron beams are also needed for X-ray generation, pumping of gaseous lasers, and surface treatment of materials. Field emission sources show great promise for these applications as they can produce current densities higher than 10 A/cm² at voltages below 100 V. Despite these promising attributes, the state-of-the art devices have produced currents less than 300 mA due to limitated array size (1–10 mm²) because of fabrication issues that result in failure or severe sub-utilization of the array. The major challenges include low yield of fabrication, large variation in gate and tip dimensions across the array, and point defects in the gate dielectric.

We have developed a high-yield process for fabrication of large-area, self-aligned, gated tip arrays with low sensitivity to processing conditions. The fabricated field emission arrays (FEAs) demonstrate average field factor >10⁶ cm⁻¹ using nanometer-scale tips (radii < 10 nm) surrounded by individual gates with 1.5 µm radius of aperture. This ensures low-voltage operation of the device and a turn-on voltage below 50 V. For reliability a thin Pt layer was deposited over the FEA and a $SiO_x/SiN_x$ dielectric stack thicker than 2.5 µm was used as the gate insulator. The Pt coating ensures chemical resistivity of the tips against corrosive gasses/ions, and the thick insulator stack limits the field inside the gate dielectric to < 150 V/µm at Gate-Emitter voltages of < 300 V. Our FEAs consisting of 320,000 tips in 0.32 cm² are capable of emitting currents as high as 350 mA at densities of ~1.1 A/cm². The device operation at higher emission currents was prevented due to plasma ignition because of the excessive outgassing of the anode. At low pressures, long-term (~3 hrs) operation not only was possible but also lowered emission voltage and gate current.




▲ Figure 1: SEM images of a fabricated array showing angle-view, cross-section and close-up images of a gated tip, confirming the self-aligned structure of the device and tip radius of less than 10 nm.




▲ Figure 2: Field emission characteristics of an FEA consists of 320,000 Pt-coated and gated tips with radii below 10 nm. Currents as high as 350 mA were emitted at gate-emitter voltage of 300 V.

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