A Review of Field Emission Cathode Technologies for Electric Propulsion Systems and Instruments[1]

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Abstract-Cold field emission cathodes are being considered as the electron sources for propellant ionization and ion beam neutralization in electric propulsion systems. Compatible field emission cathodes will enable the development of microscale electric propulsion systems. The hostile environment of the propulsion systems is very demanding on the cathode performance. Feasible cold FE cathode technologies are reviewed in this article. FEA cathode materials and configuration were optimized to meet the demands of this application. A cold cathode configuration is recommended as the most compatible cold FE cathode technology.

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1. INTRODUCTION

The development of microspacecraft requires the miniaturization of all on-board systems including instruments and propulsion systems. Micropropulsion systems providing less than 5 mN of thrust are currently being developed for micro- and miniscale spacecraft for primary propulsion and attitude control, and for larger scale spacecraft requiring disturbance torque compensation. Missions requiring these micropropulsion systems include LISA and ST-5. It has also been proposed to use them on fleets of microspacecraft employed to explore the rings of Saturn. Missions employing large inflatable structures like the concepts Arise and Space Solar Power (SSP) will require mini- and microscale propulsion systems for continuous disturbance torque compensation.

The miniaturization of Electric Propulsion (EP) systems and microscale instruments is limited by cathode size and power. Cathodes commonly used by EP systems include filament and hollow cathodes. Electron sources in imaging and gas analysis instruments are typically filaments. The disadvantages of these cathodes are high power and propellant requirements and dimensions not compatible with microscale systems. A Hall thruster has been developed to operate at power levels below 50 W and an ion thruster to operate at a comparable power level is being developed. Hollow cathodes commonly used with these thrusters are not scaleable in size and power to regimes compatible with these thrusters. State-of-the-art hollow cathodes consume no less than 7 W for 100 mA, 12% of the power of the propulsion system. State-of-the-art filament cathodes are being developed for FEEP systems at ESTEC with an optimistic anticipated performance of 5 mA/W. [1]

The development of microscale colloid thrusters, FEEPs, microscale ion and Hall thrusters is currently limited by cathode technology. Each of these thrusters requires electron sources for ion beam neutralization. Ion and Hall thrusters also require cathodes for propellant ionization. The development of cold cathode technologies without propellant r equirements is imperative to the successful miniaturization of these systems. Cold FE cathodes have been successfully integrated with flat panel technologies. In these systems, the pressures are 10^{-9}-10^{-7} Torr with close-spaced triode configurations and high anode voltages. The demands on these cathodes for EP and instrument applications are far greater. Operating environments could be plasmas with pressures higher than 10^{-5} Torr and dangerously high ion fluxes to the cathode surfaces. The performance demands on these cathodes for EP applications are described in Table 1 with operating environments.

Instruments and sensors with could benefit from cold FE cathode technology include scanning electron microscopes, electron beam lithography systems, mass spectrometers, pressure sensors, and accelerometers. Some of these applications will require higher energy electrons, however, in general these applications are much less demanding on cathode performance. Currents required and environment pressures will be considerably lower. The cathodes developed for EP applications can also be used in the instrument applications.

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Table 1 **Microscale thruster cold cathode applications, roles, and requirements.**

Thruster	T (mN)	I (mA)	Lifetime (hr.)	Environment
Colloid	0.001	~0.05	3000	Glycerol
FEEP	~0.001-0.1	20		Cesium
Ion	~5	100-500	3000 hr.	10^{-5}-10^{-3} Torr-Xe
Hall	~5	100-500	3000 hr.	10^{-5}-10^{-4} Torr -Xe

The two primary types of cold cathode technologies are Spindt-type and thin NEA film field emission sources. These cold cathodes require electric fields to deform the potential barrier between the emitting material and vacuum to let the electrons tunnel out of the material by Fowler-Nordheim emission.[2] Barrier height and width reduction induced by electric fields is illustrated in Figure 1. The F-N field emission equations are shown as eqns. 1-3 where the electric field is represented as F, and the work function is represented as ϕ.[2] Macroscopic electric field strengths required by these cathodes for electron emission exceed 4×10^{7} V/cm. Spindt-type cathodes require sharp structures for geometrical electric field enhancement to reduce the required applied fields. The field at the tip of the emitter is inversely proportional to the tip radius of curvature. This type of cathode is natural candidate for microfabrication because reducing dimensions reduces operating voltages. Low operating voltages (<100 V) are preferred to minimize the frequency of arcing events and energy in the events, to reduce the flux of ions bombarding the cathodes, and to reduce the voltage required by the electronic drivers.

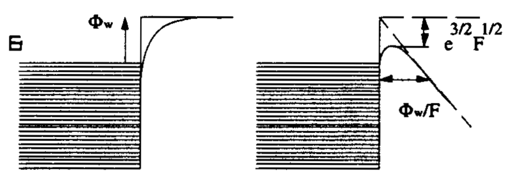


Figure 1 Potential energy diagram for electrons at a metal surface, without (left) and with (right) an applied electric field, F.

$$J_{FN}(F) \approx a_{fn} F^2 \exp(-b_{fn} / F) \qquad (1)$$

$$a_{fn} = \frac{1}{16\pi^2 \hbar t(y)^2 \Phi} \exp\left(\frac{16Q}{3\hbar}\sqrt{\frac{2m}{\Phi}}\right) \approx (116\phi)^{-1} \exp\left(\frac{14.3994 b_{fn}}{\phi^2}\right) \qquad (2)$$

$$b_{fn} = \frac{4}{3\hbar}\sqrt{2m\Phi^3}\upsilon_o \approx 0.642\phi^{3/2} \qquad (3)$$

NEA films are doped semiconductors used as field emission sources in a planar geometry. These films can be deposited on a roughened or smooth conducting substrate (metallic or n-type doped silicon). The dopant density in the NEA films is critical to the conductivity of the films and the transport of the electrons through the conductor/semiconductor interface. Across this interface, a constant Fermi energy must be maintained. This is achieved by electrons flowing into the conductor to raise the Fermi level of electrons relative to the conduction band of the NEA film. An electron depletion region is then formed in the NEA film with a thickness which is inversely proportional to dopant concentrations. Significant electric field enhancement occurs in the film because of this depletion region, which reduces and thins the Schottky barrier at the interface and facilitates electron tunneling from the metal into the conduction band of the film. This internal field emission process is discussed in more detail by Lerner et al.[3] A roughened interface generates further field enhancement and barrier narrowing and reduction.[4] The conduction band energy of NEA films is above the vacuum potential; therefore, the electrons pour out of the films into the vacuum with relatively low applied electric fields.

The hostile environments created by electric propulsion systems can significantly limit the lifetime and compatibility of cold cathodes and EP systems. Ions are generated between the tips and gate electrodes and near the thruster in charge-exchange collisions. The CEX ions are accelerated through 20 V between the cathode and plasma. The flux of this ion population to the cathode is orders of magnitude higher than the local flux of ions. Recent studies showed that Spindt-type cathodes can operate in higher pressure environments if operated below the voltage threshold for sputtering and NEA films have proven to be incredibly robust in simulated EP environments. Post emission acceleration schemes have been proposed and developed to decouple electron energies from gate electrode voltages. With these schemes electron energies can be increased without sacrificing cathode lifetime to increase space-charge current limits. Electrode configurations have also been proposed to shield the electron emitting surface from bombardment by ions originating near the thruster. This configuration can significantly increase tolerable operating voltages and cathode lifetime. Current limiting architectures have also been developed to increase cathode lifetime by suppressing arcs between the emitting surface and the gate electrode.

The performance of field emission cathodes in EP and instrument environments depends on the emitter and electrode geometry, materials, architecture, and operating voltages. This paper presents a review of thin NEA thin film and Spindt-type cathodes, current limiting architectures, electron accelerating schemes, ion filter schemes, and recommends directions for technology development to meet the demands of instrument and electric propulsion system requirements.

2. REVIEW OF FE CATHODE TECHNOLOGIES

The most mature and promising FE cathode technologies are reviewed in this section. The fabrication, configuration, materials, and performance of Spindt-type and thin NEA film cathodes are presented and compared. The performance of the cathodes in different environments is also discussed. Current limiting architectures used to suppress arcs between the tips and gate electrodes and increase lifetime are also discussed and compared. Electron acceleration schemes developed are presented and compared. A scheme for protecting the tips from ions generated in plasma sources is also presented in this section.

NEA Film cathodes

The NEA film technology is much less mature than Spindt-type cathode technology. The performance of these cathodes is not as well understood as Spindt-type cathodes, therefore models are not available for material and configuration optimization. These cathodes have been tested primarily in diode configurations with a planar anode and no gate electrode, therefore, the efficiency of these devices has rarely been ascertained. Cathodes tested with gate electrode configurations have demonstrated low efficiency and high operating voltages with respect to Spindt-type cathodes.. However, few attempts have been made to miniaturize the triode configuration to dimensions which are similar to Spindt-type cathodes, to increase efficiency and reduce operating voltages. The most promising aspects of these cathodes are low electric fields required for emission, and their robust nature in elevated inert pressure environments and with high operating voltages. The NEA film cathode technologies are presented in this section with fabrication process and materials, and compared by current densities and electric fields. These films have also been used as coatings on the Spindt-type cathode to improve cathode robustness and reduce operating voltages. The effects of these films on FEA cathodes are also discussed after the review of Spindt-type cathodes.

Diamond films-The original research on field emission from NEA films focused on diamond films. It was thought that diamond would be the ultimate FE cathode material because of its NEA property, robust nature, and chemical inertness. Diamond films have been deposited using hot filament and plasma enhances chemical vapor deposition. Polycrystalline diamond has demonstrated turn-on at $2.2x10^5$ V/cm.[5] Blyablin et al. demonstrated 500 mA/cm^2 from diamond film cathodes.[6] Cathodes with diamond grit have been microfabricated with gate structures at MIT/LL.[4] With 2 μm apertures and 1 μm deep wells emission current densities of 100 mA/cm^2 at 20 V have been achieved. This current density is the highest achieved by field emission devices for such a low operating voltage, however, the efficiency of the device is low and not reliable. The current collected by the gate electrode ranged from 0.2 to 100 times the current collected by the anode.

Carbon films-NEA carbon films have been deposited at Field Emission Picture Element Technology (FEPET) Inc. using a Hot Filament Chemical Vapor Deposition (HFCVD) method. These cathodes have demonstrated impressive performance in UHV and in simulated thruster environments. A 40 mA current was measured at FEPET Inc. from a 25 mm carbon film cathode (16 mA/cm^2) with an extraction field of $6.7x10^4$ V/cm.[7] An emission current density of 100 mA/cm^2 was achieved by FEPET with an extraction field of less than $1.2x10^5$ V/cm. These cathodes have demonstrated permanent performance degradation in oxygen environments; however, they have been operated successfully in simulated thruster environments with a Xe pressure of $2x10^{-6}$ Torr. The cathode configuration tested is illustrated in Figure 2b. The performance of these cathodes was not affected by the xenon environment, even with operating voltages greater than 800 V. These cathodes turned on in the xenon and UHV environments no differently. With a gate electrode 100 μm from the emitting surface, the gate electrode current was excessively high; only 20% of the current escaped through the gate electrode to the anode. It is anticipated that the efficiency of these cathodes will significantly improve with gate electrodes microfabricated and positioned approximately 1 μm from the film.

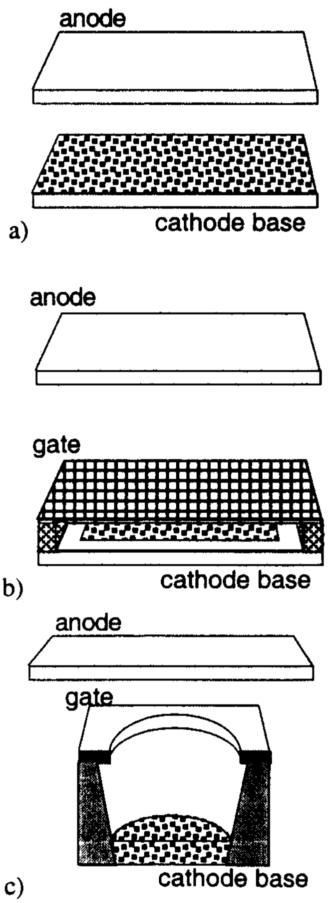
Si/Cs/O nanoclusters-Thin NEA films of Si/Cs/O nanoclusters have been deposited at LLNL by supersaturated thermal vaporization of Si and Cs in an oxygen background gas.[8] These films can be deposited onto conducting or semiconducting substrates. The thickness of the films is typically 9 nm with 5 +/- 2 nm radii clusters. The packing density of the clusters is so high that they resemble a dense array of sharp tips. The turn-on fields of these cathodes is ~8.7 V/μm for 9 nA of current. The probe diameter which applied the high voltage was 3 mm; however, the emitting area of the film was uncertain. The current density at 8.7 V/μm was at least 0.127 mA/cm^2. It has been demonstrated that these films are unaffected by air exposure and are stable to high temperature annealing (550 °C).

NEA tip cathodes

BN-Diamond-Boron nitride films demonstrating NEA have been deposited on n-type polycrystalline diamond at Sarnoff Corp. by laser ablation and subsequent laser annealing.9 The BN film is 100 nm thick on a diamond film which is 25 μm thick on a Si substrate. The size of the diamond crystallites ranges from 5 to 15 μm. The emission current can vary through 2 orders of magnitude on the surface as measured by a 0.5 mm probe. This probe has measured current densities of at least 5 μA/cm^2 at $2.4x10^5$ V/cm^2 and 500 μA/cm^2 at $4.2x10^5$ V/cm^2.

Localized current densities can be as high as 2 A/cm^2 at emission sites. These cathodes have been turned on without conditioning in 10^{-6} Torr of air and have demonstrated stable operation in pressures as high as 10^{-4} Torr.[10]

Diamond tips-Diamond tips have been microfabricated in a gated configuration by Kang et al. with a record low turn-on voltage of 0.7 V for a 2x2 tip array.[11][12] These cathodes are fabricated using a molding and self aligning gate techniques. The diamond is deposited into a mold by Plasma Enhanced Chemical Vapor Deposition (PECVD). The cathode configuration is shown in Figure 2e. The PECVD fabrication parameters are controlled to achieve a small sp2 content in the diamond film and the diamond is doped with boron to improve its performance. The tips are naturally sharpened when they are exposed through the SiO_2 during etching. This 2x2 diamond tip array turned on at 10^4 V/cm. At less than 5 V, 4 μA were measured. from the cathodes in 10^{-6} Torr. The turn-on voltages for these cathodes is the best ever reported. The base of these cathodes is 4.2 μm. With 6 μm centers, packing densities of the tips of 10^7 tips/cm could be achieved.



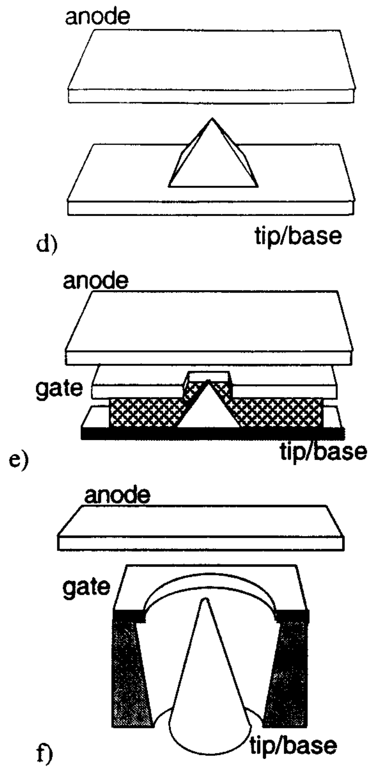


Figure 2 Thin film cathode configurations-a) thin-film cathode in diode configuration, b) Macro gated structure, c) microfab gate structure with thin film, d) diamond pyramids on diamond, e) microfab gated structure with diamond tip f) Spindt-type cathode.

Spindt-type cathodes

Field emitters were originally developed and tested as electrochemically etched tungsten tips. They were operated in field emission microscopes in diode configurations to study surface phenomena. In these configurations the gap between the tip and anode was on the order of 1 cm and operating voltages exceeded 1 kV. In 1968, Spindt microfabricated gated structures to obtain the electric fields required for field emission, $>10^7$ V/cm, at voltages below 100 V. Spindt-type cathode technology is so mature that performance models are available to determine the cathode dimensions required for specific materials and performance requirements. Mo and Si cathodes are currently available in television flat panel displays. Many other materials have been used with varying levels of success. GaAs cathodes have also been microfabricated with tip and wedge configurations. The advantages of Spindt-type cathodes over current thin film and wedge cathode technology is higher current densities, lower operating voltages, higher efficiency, and lower power operation.

Molybdenum FEAs-The Spindt-type cathode is the class of field emission cathodes which consists of microfabricated tip and gate electrode configurations as shown in Figure 2f. Spindt-type cathodes were first fabricated with molybdenum tips and gate electrodes.

Spindt-type cathodes are traditionally fabricated using the process outlined in Figure 3. An SiO_2 film and then Mo film are deposited on a Si wafer. The electrode films are deposited with electron beam evaporators or sputtering sources. The Mo is patterned and etched to form the gate electrode. The SiO_2 is then etched to the Si wafer, forming arrays of well structures. The tips are then deposited into the wells, and can be coated with different materials. The aperture dimensions and packing densities depend on the patterning process. Three commonly used techniques are photolithography, electron beam lithography, and interferometric lithography. Packing densities for Mo cathodes greater than 10^8 tips/cm^2 have been achieved using these processes.[13][14] The tips are commonly conditioned by cleaning and sharpening in plasma environments, which also improves the uniformity in tip radius across the array. Mo cathodes are conditioned in H_2+10% Ne plasmas to clean the cathode surface and sputter the tips to improve the uniformity in tip radius across the array. Tip radii smaller than 40 Å are attainable in well conditioned arrays.[13] Mo FEA cathodes have demonstrated current densities greater than 2000 A/cm^2, the highest current densities to-date.[15][16]. Spindt has operated Mo cathodes at efficiencies as high as 120 mA/mW. Mo arrays have been fabricated with 0.32 µm tip-to-tip spacing and 0.16 µm gate aperture diameters at the Lincoln Laboratory at the Massachusetts Institute of Technology (LL/MIT).[14] This array of 900 tips emitted a record low 1 µA of current at 25 V. The voltage dropped to 10 V when the tips were coated with cesium, however this coating is never stable during operation. The performance of these cathodes returned to the pre-cesiation levels within 24 hours.

FEA cathodes can be very sensitive to operating environment. Adsorption of the ambient gas can change the work function of the surface, and ion bombardment can change the tip radius of curvature. It has been shown that the performance of Mo cathodes will degrade as the vacuum chamber pressure is increased from 10^{-9} to 10^{-5} Torr of air, however, this change is temporary if only work function changes occur. The cathode performance returns to the pre-exposure performance when the pressure is returned to 10^{-9} Torr.[17] This performance was observed from a cathode operating at 20 µA and 115 V. Mo cathodes have demonstrated similar results with nitrogen and argon environments. During exposure to hydrogen at 10^{-6} Torr, performance improvements have been observed.[17] Mo cathodes tested in xenon environments similar to thruster environments showed that the gate electrode voltage must be below 50 V to avoid permanently damaging the cathodes with pressures at 2×10^{-5} Torr.[18] The xenon environment did not change the work function of the surface.

Silicon FEAs-Silicon cathodes are fabricated with a process somewhat reverse to the Mo cathodes. The tips are etched in the Si wafer and then the insulator and gate electrode films are deposited and etched into structures with arrays of tips in well structures. It has been shown that the optimal performance in current and efficiency is obtained when the tip is just protruding through the gate electrode.[19] Figure 4 shows the process used to microfabricate Si cathodes. Si cathodes are sharpened in oxygen plasmas and cleaned in a Cl+H_2 plasma. The advantage of the Si cathode fabrication process is that it is easier to deposit films on the tips. Si cathodes have been fabricated with tip radii as small as 40 Å and gate aperture radii as small as 250 nm. Linear cathode arrays fabricated at MCNC demonstrated 3 mA from 100 tips at 85 V.[20] The tip-to-tip spacing in that cathode was 20 µm. Si cathodes fabricated at the University of Michigan demonstrated 20 mA at 50 V from 100 tips. The tip radii were 8 nm and the gate aperture radii were 250 nm. A current of 2.5 µA has also been demonstrated at 25 V from a single tip.[21]

The performance of silicon cathodes is also sensitive to operating environment. Silicon cathodes have been tested at MCNC in oxygen, nitrogen, and helium environments with pressures up to 10^{-6} Torr during which the cathode performance degraded only temporarily in the higher pressure environments due to work function changes.[22][23] When the cathodes were tested in 2×10^{-5} Torr of xenon, the operating voltages were limited to below 60 V to avoid permanently sputter damaging the cathodes.[18] The xenon environment did not change the work function of the surface.[18]

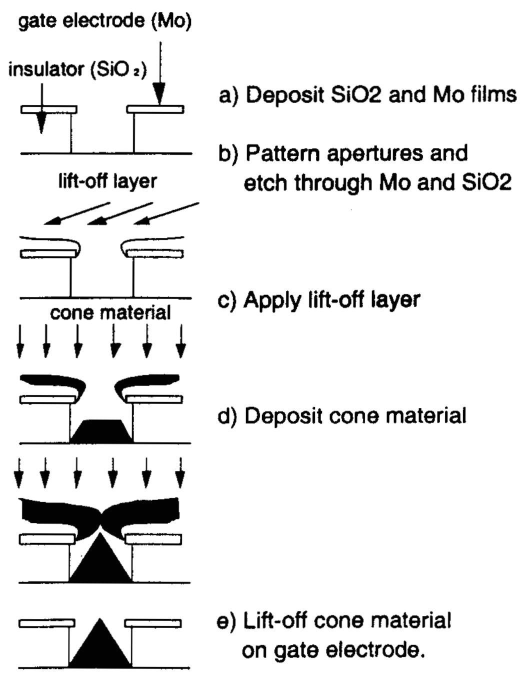


Figure 3 Fabrication process of Spindt-type FEA cathodes.

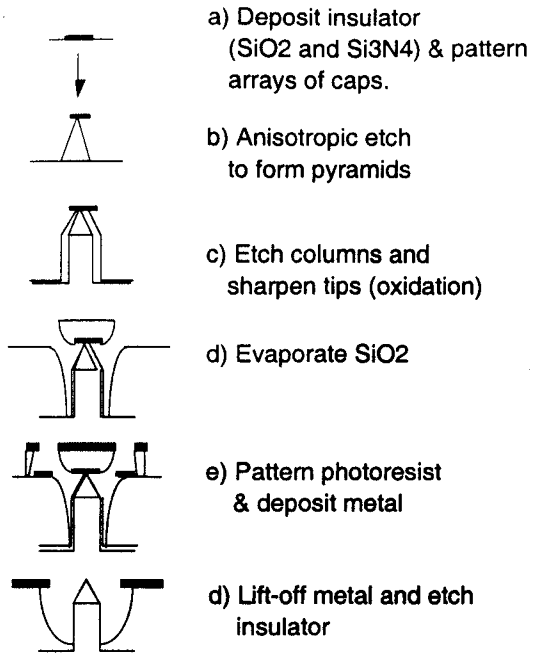


Figure 4 Fabrication process of Spindt-type Si-based FEA cathodes.

Gallium Arsenide-GaAs cathode fabrication is very similar to Si cathode fabrication.[24] The work function of these cathodes is 4.07 eV and is very similar to the work function of doped Si cathodes at 4.05 eV. The advantage of GaAs over Si is its better heat dissipation. Higher currents per tip can then be tolerated. Joule heating can also be an order of magnitude lower for wedge structures than microscale tip structures. Tip radii achievable with chemical and RIE processing for GaAs cathodes are 5-40 nm, and are comparable to Si and Mo microscale tip cathodes. However, higher operating voltages would be required for the same wedge and gate aperture radii as a tip structure because there is less field enhancement for these structures. GaAs FE cathode technology is very promising. These cathodes should be microfabricated with integrated gate electrode structures so that their performance can be compared to the Spindt-type Mo and Si cathodes.

Metallic Coatings on FEAs-Films have been deposited on Si and Mo cathodes to improve their performance. Operating voltages for Mo cathodes were decreased by 30-40% by coating them with Ti, Zr, and Hf films.25 The work functions of these materials are Mo [3.35 eV], Si [4.05 eV], Ti [4.0 eV][26], Zr [3.9 eV][26], and Hf [3.8 eV][26]. The decrease in operating voltages can be attributed to work function reductions. The Linfield Research Institute has lead the effort on HfC and ZrC FE cathodes. Single carbide tips have demonstrated performance superior to Mo and W cathodes in field emission microscopes.[27] Carbide films on Mo, W, and Si cathodes significantly reduced operating voltages for the same emission current.[28] ZrC films on Mo FEA cathodes has reduced operating voltages by 44 %. HfC coatings reduced the operating voltages of Si FEA cathodes by 50%.[19] The reduction in operating voltages can be attributed to the lower work functions of the carbide films. The work functions of ZrC and HfC has been estimated to be 3.3-3.5 eV. Higher emission stability at higher currents and voltages have been demonstrated with these films in UHV and in much higher pressure environments relative to Mo and Si cathode performance.[27] Currents as high as 4 mA have been measured from a single ZrC tip.[27]

NEA Films on FEAs-Mo and Si Spindt-type cathodes have also been coated with NEA films discussed in the preceding subsection. A diamond-like carbon film coating on a Mo FEA cathode with 900 tips reduced turn-on voltages from 80V to 65 V and increased emission stability.[29] The DLC film was deposited using a layer-by-layer technique using plasma enhanced chemical vapor deposition. The Mo work function was assumed to be 4.5 eV and the effective work function of the DLC coated Mo tips was determined to be 2.6 eV. Si cathodes have been coated with polycrystalline diamond by hot filament chemical vapor deposition to improve their performance.[5] Operating voltages dropped by more than a factor of two post diamond deposition. A comparison between several cold FE cathode technologies is presented in Table 2 with available data.

Table 2 Characteristics of cold field emission sources with different cathode configurations.

Config.	Material	Φ (eV)	J (mA/cm^2)	E (V/cm)	I (mA)	V_g (V)	#Tips	Area (cm^2)	Source[ref]
f	Mo	4.35							SRI Int.
f	Mo	4.35			0.001	25	900		MIT/LL[14]
f	Si	4.05			3	85	100		MCNC
f	Si	4.05			0.0025	25	1		21
f	HfC	3.3-3.5							
e	BN/Di		0.5	4.2×10^5					
e	Di			10^4	4×10^{-5}	0.7	4		Vanderblt[12]
c	Di		100			20			MIT/LL[4]
b	C		100	1.2×10^5					FEPET[7]
f	DLC/Mo	2.6							
a	Si/Cs/O			8.7x10					LLNL[8]
d	GaAs	4.07							

Current Protection Schemes

Arcing between the gate electrode and emitting surface is the most common failure mode of FEA cathodes. FE cathodes are more susceptible to arcing between the tips and gate electrodes with higher operating voltages and pressures. An arcing event can destroy a single tip and project tip material to cause additional arcing nearby. Some arcing events can cause a short between the gate and tips to destroy the cathode. Several current limiting schemes have been proposed and developed. The cathodes can be fabricated on highly resistive substrates which effectively provide a resistor in series with each tip in an array.[30] The disadvantage of this scheme is the amount of power consumed in the substrate by resistive heating. Semiconducting Si wafers provide the advantage of high resistance at low temperatures and low current and decreasing resistance with increasing current and temperatures. In this configuration, the cathodes are protected during start-up or low current operation only. Field Effect Transistors (FET) have also been used to suppress arcing.[31] These structures significantly limit the packing densities of the microtips. The most efficient method of arc suppression is the VErtical CurrenT Limiting (VECTL) architecture.[32] This configuration is shown in Figure 5. The trench and column dimensions have been optimized for packing density and breakdown voltages. Using this architecture, FEA cathodes have been fabricated with a packing density of $5x10^7$ tips/cm^2. This configuration consumes negligible power.

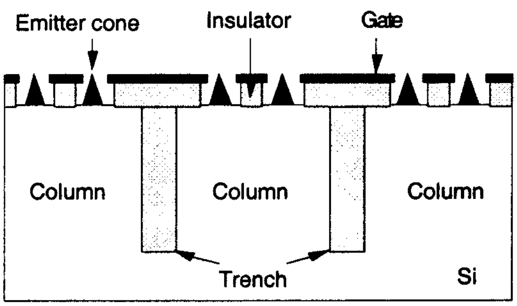


Figure 5 FEA cathode with VECTL architecture.

Ion Filtering Scheme

Another failure mode of FE cathodes in elevated pressure environments is tip blunting from ion bombardment. The cathode current is exponentially dependent on the tip radius, therefore extremely small changes in tip radius can cause significant changes in current. One ion population originates between the tips and gate electrode, and another population originates near the thruster in CEX collisions between ambient neutrals and beam ions. The gate electrode voltages will be limited to sputtering threshold voltages to prevent local ions from damaging the tips. The CEX ion flux to the cathode tips will be orders of magnitude greater than the local ion flux. Two methods for protecting the tips from the CEX ions have been recommended. In one scenario, the cathode is enclosed by a membrane which only allows the electrons to pass through it. Diamond or boron nitride screens can be used. This option is very expensive. High electron energies (> 5keV) are required to penetrate through the membrane and a significant amount of energy is deposited in it. The second option is an electrostatic shield. A Cathode Lens And Ion Repeller (CLAIR) consists of three electrodes in addition to the gate electrode as shown in Figure 6. The middle electrode, V_2, is at the highest applied voltage to repel ions when entering the cathode. The first and third electrode prevent electrons from entering the cathode and focus the electron beam through the high voltage (100 V) electrode. This electrode configuration can also be used to accelerate or decelerate the electrons emitted through the gate electrode.

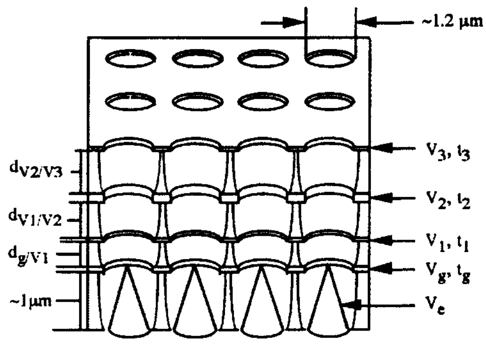


Figure 6 Cathode Lens And Ion Repeller (CLAIR) configuration.

3. REQUIRED ADVANCES IN TECHNILOGY

There are NEA films and FEA cathodes which are promising candidates for the extreme environments generated by electric propulsion systems. The NEA films are incredibly robust, therefore, they have the potential of long lifetime. However, before their advantages are to be realized, they must be deposited in gated structures similar to those used in the Spindt-type cathodes. This configuration will significantly reduce operating voltages and the power consumed by the gate electrodes. Once efficiency evaluations can be conducted, the performance of these cathodes can be compared against the Spindt-type cathodes and the advantages can be properly weighed. The diamond cathodes fabricated by Kang et al. are incredibly promising, however, these cathodes must be fabricated with a much larger number of tips to generate at least 100 mA/cm^2.

The FEA cathode technology is so mature that the cathode dimensions and materials required for the application can be predicted. In the final cathode design, the VECTL architecture and CLAIR configuration are recommended. CLAIR will allow operating voltages near the threshold voltage for sputtering. Without CLAIR the tolerable operating voltages are reduced by about 20 V which corresponds to a difference in cathode current and therefore cathode size which is several orders of magnitude. The effect of CLAIR and materials on cathode current densities are shown in Figure 7.

Figure 7 shows the performance limitations of FEA cathodes with different materials and with and without the CEX ion population bombarding the cathode. The current density objective is 100 mA/cm^2. The curves shown in Figure 7 were generated using FEA cathode performance models, performance degradation models, and sheath models to predict space-charge current limits.[18] The performance degradation model requires energy threshold for sputtering values which were experimentally determined using the FEA cathodes. Current density vs. gate electrode voltage is shown for Si, Mo, and HfC/ZrC cathodes with r_g=2000Å, r_t=40Å, Δs=2, β_g=0.26 and a packing density of 5x10^7 tips/cm^2. These cathode dimensions are optimistic but not unrealistic. The packing density was limited by the VECTL architecture configuration, not the cathode fabrication. The limits on the gate electrode operating voltage depend on cathode configuration, materials, and environment. The voltage limits on Si and Mo cathodes with the configuration defined in a xenon environment at 2x10^{-5} Torr are given in Figure 7. The operating voltage limited by the flux of ions generated between the tips and gate electrode are defined by 'V_{gth} for Si/Mo w/o CEX ions'. The possible operating voltages and corresponding current densities for the cathodes are defined by the J-V curve between 100 mA/cm^2 and V_{gth}. Si cathodes with this configuration could operate between 40 and 52 V and satisfy the performance requirements. Mo cathodes with this cathode configuration will be able to deliver 100 mA/cm2 at voltages below V_{gth}. The Mo work function and sputter yield are too high.

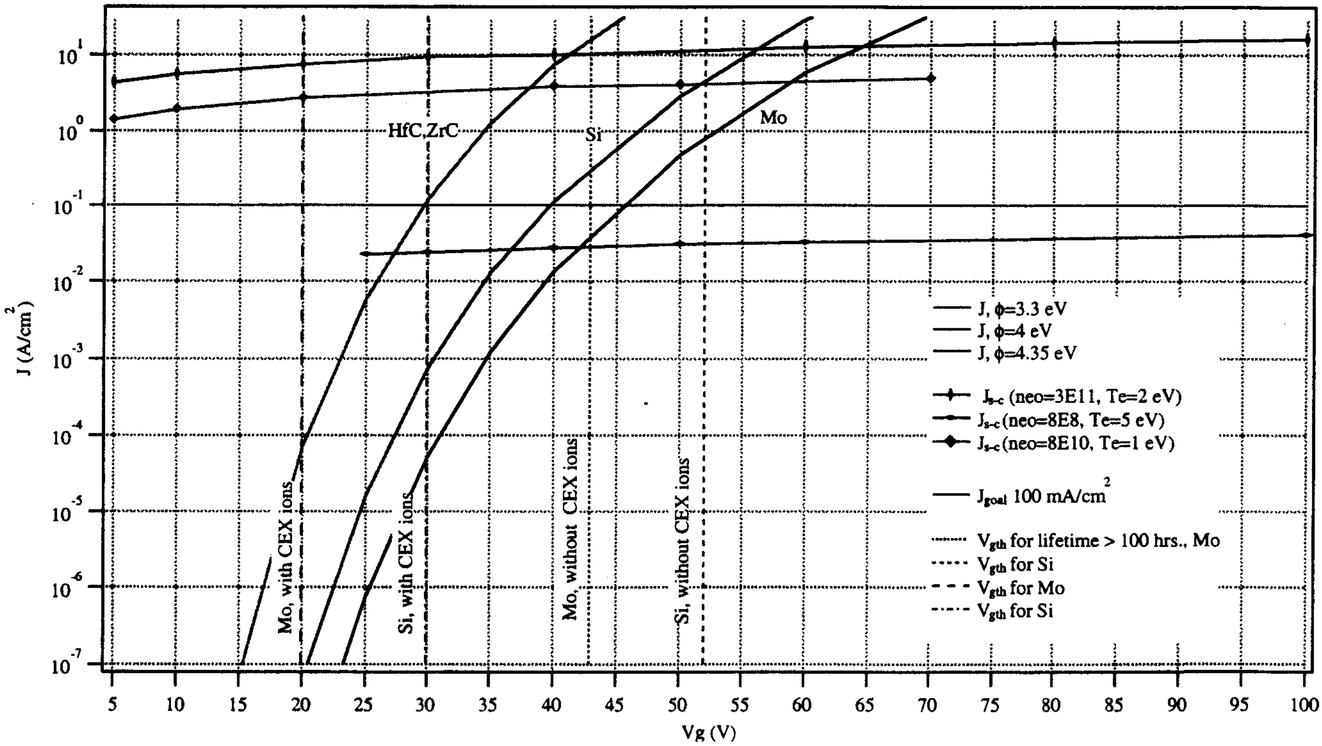


Figure 7 Current density limitations, requirements, and capabilities for Mo, Si, and HfC field emission array cathodes if P=2x10^{-5} Torr of Xe, r_t=40Å, r_g=2000Å, pd=5x10^7 tips/cm^2, β_c=0.26, and Δs=2.

If the CEX ion population is also considered in the performance degradation rate calculations the operating voltages are further limited. The additional population of ions originating near the thruster, charge-exchange ions, further limits the operating voltages, V_g, by 20 V because they will be accelerated between the plasma to the gate electrode by 20 V before being accelerated between the gate electrode and tip. This population of ions can bombard the cathode with a flux which is a few orders of magnitude higher than the flux of ions generated between the tips and gate electrode. Either the cathode must be shielded from this population of ions or cathode operating voltages will be limited to 20-30 V for the required performance decay rates as shown in Figure 7. With CLAIR, the CEX flux is eliminated and higher operating voltages are tolerated.

5. CONCLUSIONS

A review of the current state-of the art cooled FE cathode technology was conducted. Spindt-type cathode, NEA films and tips, and NEA films on Spindt-type cathodes were investigated in the review. While planar NEA films are incredibly robust, they have not yet been optimized at low enough voltages and high enough efficiencies to compete with Spindt-type cathodes. The performance of NEA films on Spindt-type cathodes look very promising, especially in higher pressure environments. NEA films are typically very sensitive to the chemical processing required to microfabricate gated structures. And the gate structures are sensitive to the high temperatures typically required to deposit the NEA materials. The results obtained by Kang et al.12 are the most promising for this technology. Fabrication of an array of these cathodes with enough elements to generate 100 mA/cm^2 remains to be done.

The Spindt-type cathode is the most mature FE cathode technology. Performance models were used to optimize cathode materials and configuration to meet the demands of the propulsion systems and deliver the required performance. The recommended dimensions are presented in the preceding section. These dimensions are optimistic, but not unrealistic. The performance requirements of the propulsion systems are current densities at least 100 mA/cm^2 and less than a 10% drop in current during 100 hours of operation in $2x10^{-5}$ Torr of xenon. Even with these optimistic cathode dimensions Mo cathodes will not be able to meet these performance requirements. The work function of Si is significantly lower than it is for Mo and the energy threshold for sputtering is significantly higher, therefore, with the optimistic dimensions, a Si cathode can meet the performance requirements only if CLAIR is used to protect the tips from CEX ion bombardment.

The recommended material for the Spindt-type cathodes is either HfC or ZrC. The most success has been demonstrated from Mo and Si cathodes with carbide films. With these materials the current densities will be greater than 100 mA/cm^2 with the recommended cathode configuration, operating voltages less than 30 V, and negligible performance degradation rates. If HfC or ZrC cathode material is used CLAIR is not required. However, both CLAIR and the VECTL architecture are recommended for maximum lifetime and performance.

Acknowledgements

The author would like to gratefully acknowledge the sponsors of this research and the contributions made by experts in the field of field emission technology. The authors of many of the papers referenced in this article contributed information and advice in addition to that which was published in their articles. Their time and advice was greatly appreciated. The review of cathode technologies presented in this article was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract by the National Aeronautics and Space Administration.

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