Experimental Results of Testing Electron Field Emission Cathodes for Spacecraft Applications

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ABSTRACT

We present a review of field emission cathode testing being conducted on a particular cathode type, a Spindt cathode, in anticipation of use of such cathodes for spacecraft applications. Field emission cathodes have been previously recommended as candidates for reducing spacecraft charging and as highly efficient, low-mass, electron sources for high current space applications such as electrodynamic tethers.

Operational data were gathered using off-the-shelf ultra-high vacuum cathodes to aid in the design of a prototype cathode controller for space use and to advance the understanding of operational limits when cathodes are used on spacecraft. Future tests will make use of the prototype controller to explore current emission changes and operational characteristics affected by exposure to different environments. The feedback controller was designed to implement a simple cathode control system and safety features to protect cathodes from sudden environmental changes. Design considerations for various spacecraft applications and suggested cathode design improvements for space applications are described along with proposals for space flight tests of cathodes.

1 INTRODUCTION

We present an introduction to Spindt cathode field emission technology developed at SRI with a focus on possible space applications. The low power and light weight of Spindt cathodes make them ideally suited to space applications requiring electron emission, while the robustness and efficiency of the devices provide the ability to emit currents from nanoamps to tens of milliamps per device tip. Grouped in arrays from a single tip to millions of tips per square centimeter, Spindt cathodes provide a mechanism for emitting controlled currents from nanoamps to well above the 1 amp level from a low-power, cold cathode device limited only by thermal and space charge effects.

After an initial discussion on Spindt cathode characteristics, we present examples where Spindt cathodes represent an alternative to traditional electron emission technologies in applications such as spacecraft charge control, electrodynamic tether propulsion, ion and plasma propulsion, and electron beam emission. These application areas have motivated SRI to pursue in-house testing of cathodes with a specific interest in acquiring the engineering and operational insights necessary to implement these space applications. The progress of this testing and discussion of future plans in these application areas are described.

2 SPINDT CATHODES BACKGROUND

SRI has been involved in research into the design of vacuum microelectronic cathodes for many decades. The initial development of field emission cathodes resulted in the development in the late 1960s of the Spindt cathode [Spindt, 1968] and in numerous patents on this technology during the 1970s and beyond. Most of the effort in the early decades involved fabrication techniques for single tip cathodes and small arrays. Since that time, SRI has made many improvements in the basic cathode structure and the robustness of arrays of cathode tips. The results of this research and development have been superior device characteristics in areas such as emitter tip density, emitter tip current capacity, and device lifetime. For example, lifetime tests have shown continuous operational life of up to eight years, with the test being terminated because of equipment failure, not a cathode failure. The references Spindt et al. [1991] and Brodie and Schwoebel [1994] are recommended for detailed background on emitter array capabilities and technology development across the gamut of field emission applications throughout the 1980s and 1990s both at SRI and at other research laboratories.

The development of emitter arrays remains an active area of research driven primarily by applications in the areas of flat panel displays and rapid turn-on, high current electron sources. Figure 1 shows electron micrographs of Spindt cathode tips and a section of one type of cathode array.

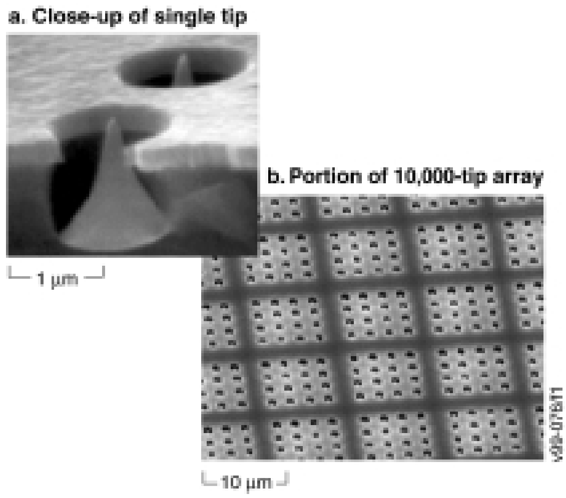

Figure 1. (a) Electron micrograph close-up of Spindt cathode tips, and (b) close-up of a section of a cathode array.

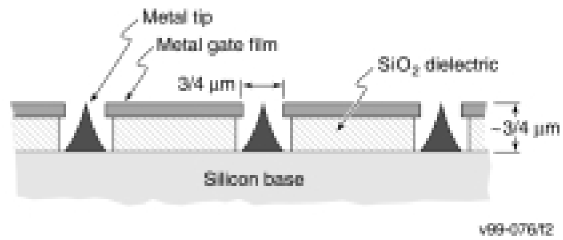

Figure 2. Schematic of a Spindt cathode array.

Basic SRI Spindt cathode emitter arrays consist of an insulating layer sandwiched between two conductors, with an array of holes in the top conducting film and in the insulating layer. The top conductor is referred to as the *gate*, and the lower conductor as the *base*. The arrays can be manufactured on any flat, smooth, ultra-vacuum-compatible substrate, either insulating or conductive. The emitter tips are fabricated in the array of holes using thin film deposition techniques (see schematic in Figure 2), and have been fabricated with submicron hole spacing, or packing densities of over 5×10^7 tips/cm^2. For such a cathode structure, adjusting the voltage of the gate layer relative to the emitter tips controls the emission level. Because of the small scales involved, only small voltages (typically less than 100 volts) are required to control emission from each tip. Per-tip electron emitting capacities of well over 100 microamps have been demonstrated with single tips, resulting in a theoretical emitted current density of 5000 amps/cm^2 for arrays with packing densities at the levels that have been demonstrated.

With such high current densities and the inherent small size and small mass of microfabricated devices, Spindt cathodes have excellent characteristics for space applications. Nonetheless, to have an advantage over existing technologies with regard to space applications, a number of additional characteristics are highly desirable. These include not only low mass and small size, but also low power consumption, clean operation, no use of expendables, high efficiency, long lifetime, and a large operational temperature range. Spindt cathodes clearly have small size and low mass by nature of their microfabricated structure, and tests have shown that they can exhibit very long operational lifetimes. The true value of Spindt cathodes as electron emitters in space is further demonstrated by the fact that these devices do indeed have extremely low power requirements, extremely efficient operation, extremely clean operation, and require no expendables. Furthermore, Spindt cathodes have been operated over temperature ranges from approximately –270° C to over 400° C. In essence, Spindt cathodes are ideally suited for space applications.

To explore the efficiency and electron emission capabilities of Spindt cathodes one can use the accepted model for field emission occurring in a Spindt cathode, the Fowler/Nordheim equation, which has the form $I = (n\,a)\,V^2 \exp(-b/V)$. The variable n represents the number of emitter tips in the array. The coefficient a is related to the effective emitting area per tip and the tip geometry, where the total effective emitting area depends on the atomic-scale details of the emitter tip surface as well as the number of tips in an array. The coefficient b is proportional to the 3/2 power of the emitter work function. (See previously mentioned references for further detail.)

Rearranging the above equation and taking the log of the result produces $ln(I/V^2) = ln(n\,a) - (b/V)$. A Fowler/Nordheim plot is a graph of $ln(I/V^2)$ vs. $(1/V)$, which, for true field emission, produces a straight line with a slope of *b* and a y-intercept of *ln(n a)*. Thus, experimentally obtained data from an emitter array having a known number of emitter tips can be used to determine the *a* and *b* coefficients for this type of cathode, and these coefficients can then be used to predict the performance of similar emitter arrays or to design emitter arrays to meet given sets of specifications. The experience with such emitter arrays at SRI has been that 1 microamp per tip is a very comfortable level of emission for these cathodes, and emission levels of over 100 microamps have been obtained from single emitter tips.

As an example of typical values, from the Fowler/Nordheim plot of a sample 1024-tip array, values such as $a = 9.72 \times 10^{-7}$ A/V^2 per tip and $b = 717$ V might be obtained. From such a result, the experimental data can be extrapolated to larger arrays and emission levels for purposes of considering the emission capabilities of a large Spindt cathode device in space. Figure 3 shows just such a plot of modeled emitted current versus applied control voltage for a 5-million-tip array, which could be readily manufactured with existing techniques. From the plot we see that a 0.01 amp emission current could be achieved with approximately 70 volts applied between the base and gate electrodes, and that a healthy 0.1 amp current could be emitted by such a 5-million-tip array with an increase in the gate voltage to approximately 85 volts. This plot highlights a very significant characteristic of Spindt cathode emitters, the value of SRI's integrated gate structure, which allows low voltages between the gate electrode and tips to control the emission of electrons.

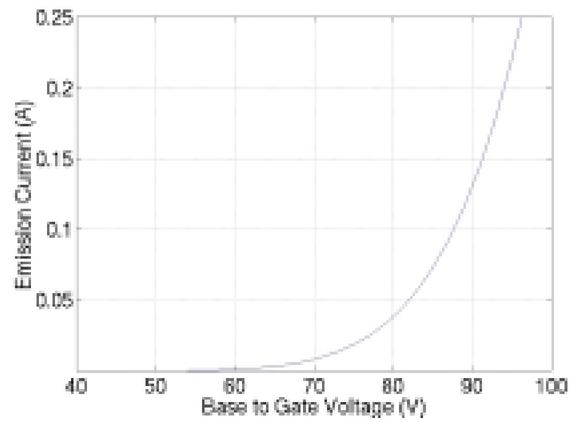

Figure 3. Modeled values of emitted current vs. gate voltage for 5-million-tip Spindt cathode array.

To emit large currents in space, the emitting source might require a large negative bias or large accelerating voltages, but these need not be part of the control voltages (or power drain) associated with operating the devices. In fact, in cases where the emitting spacecraft has a large negative bias and where minimal power consumption is desired, the devices can be operated in a “self-powered” mode. To achieve this self-powered mode the naturally occurring spacecraft-to-plasma potential difference is used to drive the electron extraction and acceleration, at least until the spacecraft frame potential reaches the minimum voltage needed for field emission to take place. This self-powered mode has been proposed for use in spacecraft charge control [Adamo, 1993] or for missions that naturally have large potentials between spacecraft components (e.g., electrodynamic tethered satellite systems). With the features of low voltage and power drain, and a possible self-powered mode, Spindt cathodes have clear advantages over traditional electron emission technologies when applied in space.

To consider the value of Spindt-cathode-based electron emitters in space, it is also useful to compare this technology with two dominant technologies typically applied to produce large electron currents in space. The examples considered here are thermionic emission (by far the most commonly used) and plasma contactors (ionized gas cloud devices). With regard to thermionic emitters, such as are found in typical electron guns, Spindt cathodes are extremely efficient, have much lower mass, and avoid most of the contamination and outgassing associated with hot cathodes. With regard to plasma contactors, not only are Spindt cathodes much more efficient and lower mass, but they do not require a hot cathode, they can respond very quickly (in the microwave frequency regime), and they have a smoothly varying output over their full operating range. More important, however, Spindt cathodes require no expendables, another major obstacle associated with plasma contactors.

3 SPACE APPLICATIONS OF SPINDT CATHODES

The many advantages of Spindt cathodes as electron sources result in a variety of possible space applications. While Spindt cathodes can literally find use anywhere electrons are needed, it makes the most sense to focus on applications where their low mass, low power, small size, and high efficiency are the greatest assets. Examples of such applications are electric propulsion, charge control, sample ionization, electrodynamic tethers, and electron beam generation. In each of these applications, Spindt cathodes can provide significant improvements over existing technologies, although only one has been used in space to date. That example is the use of Spindt cathodes for electron impact ionization of mass spectrometer samples [Curtis and Hsieh, 1986].

The term *electric propulsion* covers many propulsion concepts, and Spindt cathodes can play a role in most of these. An example application that has been investigated conceptually and is being explored experimentally by NASA's JPL is the use of Spindt cathodes as ionizers for plasma propulsion systems. They have been used in this way for terrestrial chemical analysis sample ionization for many years because they are free of outgassing and hot cathode contaminants. Another natural application is in the arena of neutralization of plasma and ion thruster plumes, where the size and efficiency are highly desirable. In summary, with regard to electric propulsion, electron field emission devices can serve in many capacities to improve existing plasma or ion propulsion systems.

Electrodynamic tethers are essentially another form of electric propulsion, but are classically grouped in a separate category because of the large physical extent of typical tether systems relative to the small size of many electric propulsion devices. However, applications involving current flow in electrodynamic tether systems such as the one depicted schematically in Figure 4 would also benefit greatly from efficient, low-power, low-mass electron sources such as Spindt cathodes. These systems consist of a conducting tether that may be connected to end bodies, and for which the motion of the tether through a magnetic field results in an EMF across the tether. This EMF can be used to drive a current through the wire if an electrical connection to the surrounding plasma is possible—for example, at the endpoints of the system. In such a mode of operation, the resulting electrodynamic drag can be used to reduce the orbit of the system or to de-orbit the system. Similarly, if a power source is available and current can be driven through the tether in the opposite direction to that which would result from the motion-induced EMF, then the interaction of the tether current with the ambient magnetic field can be used to raise the orbit of the system. (See [Banks, 1989] for further details.)

In this manner, electrodynamic tethers can be used for orbit adjusts, transfers, and de-orbiting and can be made to operate without the use of propellants. The efficiency of this process is significantly improved if the tether current can be maximized, and if the potential drop at either (or both) endpoints can be reduced. Spindt cathodes can help with both of these issues by providing very efficient electron emission and by requiring very little potential drop across the emitting device. Satellite de-orbiting is already being aggressively pursued for commercial application by Tethers Unlimited, Inc., a company with a long-life multistranded conducting tether ideal for this type of application.

In the arena of charge control, the idea of using field emission in space is not new, and one of the co-authors of this report, Richard Adamo, as early as 1993 proposed various prototype systems that would allow Spindt cathodes to be used for spacecraft charge control [Adamo, 1993]. The most natural application of electron field emitters is the control of spacecraft negative charging, found both in low Earth orbit (LEO) and geosynchronous orbit (GEO) environments. Negative charging is particularly prevalent because of the high mobility of electrons, and is readily controlled because there is no need for expendables as electrons are the only products to be emitted. However, Spindt cathode technology can also be applied to positive charge control, especially if materials are available for ionization (or by use of an equivalent but opposite polarity field ionization device, an area that SRI has also explored for many decades). The application of Spindt cathodes to spacecraft charge control is also closely related to the application of Spindt cathodes as sources for electron beam generation, where the efficient field emission of electrons from small, low-power sources is beneficial. In the case of electron beams, Spindt cathodes have been substituted for thermionic emission as a source of electrons because they avoid the problems of hot cathodes, allow very rapid switching and control, and are capable of very high currents even with the use of small control voltages.

The characteristics of charging in the GEO regime make the application of Spindt cathodes to spacecraft charge control particularly appropriate. In the GEO environment, electron currents are sufficiently low (less than 1 milliamp) that Spindt cathode control voltages of well under a hundred volts can readily produce the currents necessary to control charging, and the requisite voltage levels are available on typical GEO spacecraft. In addition, the problem on GEO spacecraft frequently involves surfaces charging negative with respect to neighboring surfaces, a problem that can be directly controlled by emission of electrons with field emission devices. Hence, the problems typically encountered on GEO satellites can be avoided by directly preventing charging to levels that lead to damaging discharges.

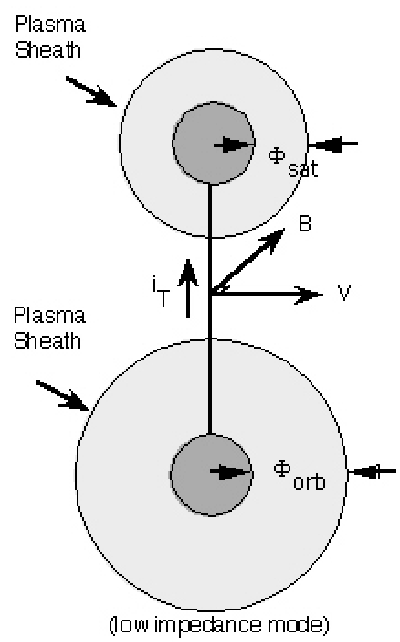

Figure 4. Schematic of an electrodynamic tether system flowing current.

4 TESTING FOR SPACE APPLICATIONS

While it is clear from the above discussion that Spindt cathodes hold great promise for space applications, there remains engineering development before this technology is fully ready for space. As a result, at SRI we have undertaken an internal research program to explore specific issues of interest for application in the space environment.

To carry out space-specific testing of cathodes, a test facility has been configured for the study of cathode characteristics and control devices. The facility is composed of an ultra-high vacuum chamber with a volume of approximately 6000 cm^3 pumped by a turbo pump system and able to achieve vacuum levels of 10^{-10} Torr (roughly equivalent to clean GEO conditions). The chamber can be baked out to temperatures of 250° C to ensure a clean starting environment for any tests, and has an attached gas manifold for use in bleeding gasses into the chamber from any of four gas sources at any time. The chamber is configured with cathode and anode mounts for multiple Spindt cathode devices to allow parallel testing of multiple devices, or comparisons between different devices under similar environments. Cathode control lines, emission currents, and environmental conditions can be monitored by a computer-controlled data acquisition system.

The purpose of this facility is not only to specifically characterize cathodes for space applications, but also to develop and test controllers for space applications. At this time, a controller for cathode emission has been designed, built, and is undergoing test. Typically, one controls field emission cathodes by means of the voltage between the control electrode (and anode or gate) and the base emitting tips. With the implemented controller, one can instead specify an emission current level, and the controller uses feedback to maintain the emission current by adjusting the voltage across the device to the required level. The prototype controller not only takes advantage of feedback control to maintain emission current to within a few percent when ambient conditions change, but also implements various protection schemes that shut down emission if over-voltage or over-current conditions develop. Figure 5 shows a plot of emission current over the period of one day (one sample per second) from recent testing with this controller. The plot shows the stability of emission over long periods of time even though chamber pressure varies but up to 20% over the course of a day. To date this controller has been used only for periods of up to 3 days, and we expect to do long-term testing to characterize its robustness over long time periods.

The controller has been implemented with an additional purpose in mind, that of investigating operational control of a cathode experiencing changes in the environment. It is known that exposure to various gasses affects the emission characteristics of field emission cathodes, and so under variable environmental conditions, such a controller is needed to maintain a desired emission level. Testing with different gases was reported by Capp Spindt in earlier work [Spindt, 1991], and provides detail on expected variations in emission characteristics over pressures ranging from 10^{-5} to 10^{-9} Torr for typical atmospheric gasses. In future work we intend to reproduce these results and study operational issues associated with controller design and operating ranges for applications that would like to accomplish active control of emitted current both at LEO and GEO pressure regimes.

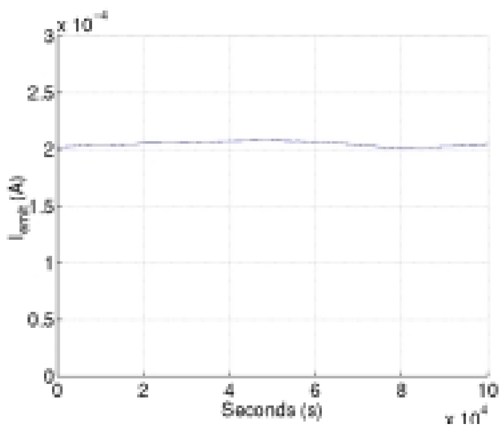

Figure 5. Plot of emitted current over time with a Spindt cathode under feedback control.

The ability to introduce gases into the test facility also allows us to explore cathode performance and control requirements in harsh environments. For example, in plasma thruster applications xenon is the gas of interest, and we will be conducting tests on effects of exposures to such gasses. The data collected will be useful not only for controller and operational design of cathode-based systems, but will also be used for comparison testing of vulnerability of different materials to different gas species. Such data will allow for improvements in cathode robustness even for cathodes not directly exposed to xenon, that is, in use for general charge control on a spacecraft.

Due to interest in use of cathodes in electrodynamic tether systems that will reach lower altitudes, SRI is also planning tests of cathodes after and under exposure to chemical species such as atomic oxygen. While SRI cathodes have been manufactured for differing applications out of different materials, existing cathode designs were not explicitly intended for space applications, and hence one could further explore optimal designs and material choices to improve applicability to specific harsh spacecraft applications. For example, standard off-the-shelf cathodes are made of molybdenum, which is expected to be susceptible to degradation at LEO atomic oxygen levels. In addition, cathode geometry changes have been proposed to address protection against particulate debris expected at LEO altitudes. For GEO applications, exposure to atomic oxygen can be avoided, protective coatings can be used to chemically protect surfaces, and particulate debris is less of a problem. However, testing and design changes are recommended for LEO applications that would experience a constant exposure to atomic oxygen and exposure to particulates.

In addition, as with any other microfabricated device, packaging and care of Spindt cathodes before they are put into operation is critical. Spindt cathodes must be kept clean and free of contaminants before use and ideally exposed to the contaminants in a spacecraft environment only after significant spacecraft outgassing has occurred. This is an issue already addressed and resolved for space applications of other technologies, such as optical systems, and so remains merely an engineering consideration to be addressed for specific applications of Spindt cathodes. Other system-level questions that may require attention for specific applications include (1) power-on procedures that improve robustness and reliability by minimizing arcing caused by contaminants and (2) current escape for applications with either high current density or low plasma density, or both (issues of space-charge-limited current escape will need to be addressed as with any source of electrons).

5 SUMMARY

We have found that the low power, low mass, and electrical characteristics of Spindt cathode field emission arrays provide a far superior alternative to existing approaches for electron emission or gas ionization in many space applications. As a result, SRI is taking an active role in testing and developing operational procedures and control systems for use of Spindt cathodes on commercial and scientific spacecraft.

SRI has established a research facility to explore the engineering and design issues associated with Spindt cathode use in space. Various applications are being considered, and SRI expertise in the development and application of Spindt cathodes to terrestrial applications is being leveraged. Primary among the applications under study are geosynchronous spacecraft charge control and electrodynamic tether system electron sources. SRI personnel with research experience in both of these applications are actively working with aerospace and university partners who have expressed interest in collaborations. In addition, SRI has been actively supporting NASA/JPL efforts to develop and pursue application of Spindt cathodes in the area of electric propulsion thrusters.

Existing internal research on the space application of Spindt cathodes is focused on cathode controllers, cathode robustness in harsh environments, and testing of cathode systems under varying environments. We hope that these efforts, combined with commercial interest and upcoming future flight opportunities, will allow the near term demonstration and testing of Spindt cathodes for space applications.

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