Space Applications of Spindt Cathode Field Emission Arrays

V. M. Agüero* and R. C. Adamo*

Abstract

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 makes them ideally suited to space applications requiring electron emission, while the robustness and efficiency of the devices provides 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 well above the 1 amp level from a low power, cold cathode device limited only by thermal and space charge effects. Spindt cathodes represent an alternative to traditional electron emission technologies in applications such as spacecraft charging measurement and control, gas ionization, plasma contact, electric propulsion, and electron beam emission.

Introduction

This paper is a summary of two presentations that dealt with the topic of space applications of Spindt cathodes, a type of electron field emission device. The presentations were joint efforts by both authors and, because of their related nature, the presentations are summarized as one article. The first presentation dealt with the question of what Spindt cathodes are and how they can be generally applied to space applications where electrons are needed. The second presentation dealt more specifically with the application of Spindt cathodes to electrodynamic tether systems where electron emitters such as Spindt cathodes can play a major role in improving the ability to flow current through a tether. This summary follows a progression similar to the presentations: After presenting background on the cathodes and field emission the focus shifts to their potential use at the negatively charged (or electron emitting) end of a conducting space tether.

*SRI International, Applied Electromagnetics Lab, Menlo Park, CA 94025

Background of Spindt Cathodes

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 numerous patents on this technology during the 1970s and beyond. Most of the effort in the early decades of development involved fabrication techniques for individual 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 a power failure, not a cathode failure. The reference Spindt et al. [1991] is recommended for detailed background on emitter array capabilities and technology development through the 1980s, and it contains further references to the history of device technology development at SRI. 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 a cathode array.

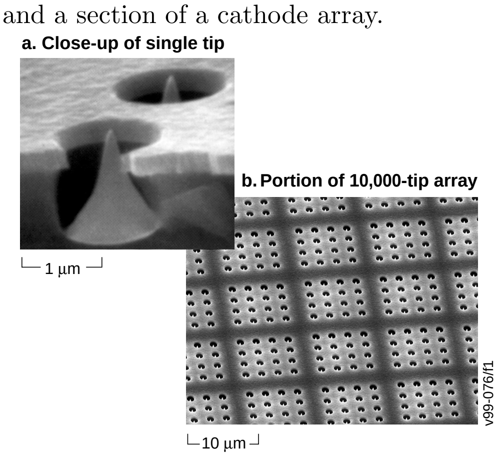

Figure 1. (a) Electron micrograph close-up of Spindt cathode tips, and (b) close-up of a section of a cathode array.

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 is 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, the emission level is controlled by adjusting the voltage of the gate layer relative to the emitter tips. 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 up to 100 microamps have been demonstrated with single tips, resulting in a theoretical capacity of 5000 amps/cm^2 for arrays.

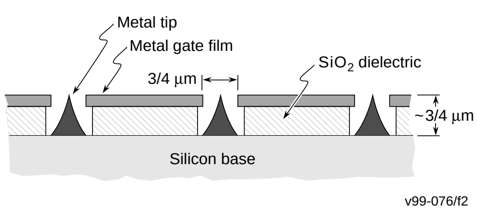

Figure 2. Schematic of a Spindt cathode array.

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.

Characteristics and Design of Spindt Cathode Devices

To explore the efficiency and electron emission capabilities of Spindt cathodes, a brief introduction to electron field emission is provided. The accepted model for field emission occurring in a Spindt cathode is the Fowler/Nordheim equation, which has the form $\mathrm{I} = (na)V^2 e^{(\frac{-b}{V})}$. 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 emitter work function. One can use a Fowler/Nordheim plot of experimental results to extract values for the a and b coefficients, which can then be used to design emitter arrays to meet given sets of specifications.

Rearranging the above equation and taking the log of the result produces $\ln(\frac{\mathrm{I}}{V^2}) = \ln(na) - (\frac{b}{V})$. A Fowler/Nordheim plot is a graph of $\ln(\frac{\mathrm{I}}{V^2})$ vs. $(\frac{1}{V})$, which, for true field emission, produces a straight line with a slope of b and a y-intercept of $\ln(na)$. 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. 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 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 easily manufactured with existing techniques. From the plot we see that a 0.1 amp emission current could be achieved with approximately 60 volts applied between the base and gate electrodes, and that a healthy 1 amp current could be emitted by such a 5 million tip array with a small increase in the gate voltage to approximately 70 volts. This plot highlights a very significant characteristic of Spindt cathode emitters, the value of SRI's gated structure, which allows low voltages between the gate electrode and tips to control the emission of electrons.

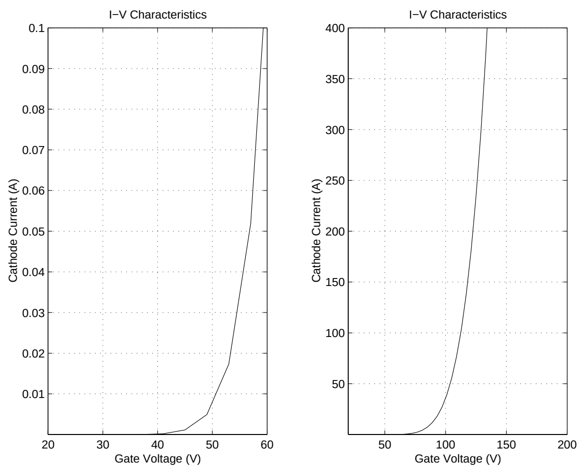

Figure 3. Modeled values of emitted current vs. gate voltage for a 5 million tip Spindt cathode array.

To emit such 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 gate electrode is biased positive relative to the cathodes, which are kept at spacecraft body potential. In this case, the system power consumption is simply the tiny fraction of the emission current that is re-collected by the gate electrode. The naturally occurring spacecraft-to-plasma potential difference drives the electron extraction and acceleration, at least until the spacecraft frame potential reaches between 50 and 100 V relative to the ambient plasma. 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 useful to compare that 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 (1) they do not require a hot cathode, (2) they respond very quickly (in the microwave frequency regime), (3) they have a smoothly varying output over their operating range, and (4) they are not strongly affected by ambient plasma conditions. More importantly, however, Spindt cathodes require no expendables, another major obstacle associated with plasma contactors.

Example Space Applications of Spindt Cathodes

The many advantages of Spindt cathodes as electron sources in space results in a variety of possible space applications. While Spindt cathodes literally can find use anyplace where electrons are needed, it makes most sense to focus on applications where their low mass, low power, small size, and high efficiency are the greatest assets. Some examples of such applications include electric propulsion; charge control and measurement; orbit adjusts, transfers, and deorbiting; sample ionization; and electron beam generation. In each of these applications, Spindt cathodes, either individual tips or arrays, can provide significant improvements over existing technologies. Some of these improvements have already been mentioned. The benefits of Spindt cathode technology to some specific space applications is discussed below in more detail.

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 is the use of Spindt cathodes as ionizers for plasma propulsion systems. Because of their small size and high current output, these devices can serve as compact, efficient ionizers that are free of outgassing and hot cathode contaminants. A terrestrial application of Spindt cathodes has for many years been as sample ionizers for chemical analysis, and their application to higher flow rate propulsion systems is a relatively straightforward adaptation. Furthermore, their rapid response makes them suitable for applications requiring rapid control. Such applications are currently being investigated collaboratively with the US military, NASA's Jet Propulsion Laboratories, and the University of Michigan's Plasmadynamics and Electric Propulsion Laboratory. As a variation of the prior use of Spindt cathodes in ground-based sample ionization systems, they have also found application in a spacecraft mass spectrometer as a low mass, small size, highly efficient ionization source. One such device was flown aboard a comet Halley flyby mission [Curtis and Hsieh, 1986]. In summary, with regard to electric propulsion, electron field emission devices can serve in many capacities to improve existing plasma or ion propulsion systems as well, and while ion sources are not the topic of this paper, ion producing Spindt cathodes have also been developed.

In the arena of charge control and measurement, the idea of using field emission in space is not new, but only became practical as a result of microfabrication techniques having evolved. One of the coauthors of this paper, Richard Adamo, as early as 1993 proposed various prototype systems that would allow Spindt cathodes to be used for spacecraft charging measurements and spacecraft charge control [Adamo, 1993]. Adamo's proposal even provided details of the operation of a self-powered spacecraft charge control system. The most natural application of electron field emitters is the control of spacecraft negative charging (found both in LEO and GEO environments because of the high mobility of electrons) and for which 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. 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 similarly, 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 gating voltages.

Finally, the last set of applications, orbit adjust, transfers, and de-orbiting, is directly coupled to the discussion of space tethers, which is the subject of the rest of this paper. It is essentially another form of electric propulsion, but 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. The discussion of this application is left to the next section.

Electrodynamic Tether Applications of Spindt Cathodes

Electrodynamic tether applications involve the use of electrodynamic tether systems such as the one depicted schematically in Figure 4. 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 reference [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 (at the end of the tether that is negative with respect to the ambient plasma) and by requiring very little potential drop across the emitting device.

Example applications for which electrodynamic tether systems would be very useful include orbit adjusts or reboosts where solar power or some energy supply is available to drive tether currents. In addition, passive tethers or tethers with minimal control systems can be used for satellite de-orbiting and for sample return applications. The case of satellite de-orbiting is already being aggressively pursued for commercial application by SRI and Tethers Unlimited, Inc., a company with a long-life multistranded conducting tether ideal for this type of application. Spacecraft charging or charge control is an additional application that could take advantage of both Spindt cathodes and tether systems to improve performance, since tether EMF can be used to drive significant currents to or from a spacecraft as desired. Similarly, power generation and VLF signal generation are applications that would benefit from higher currents made possible by efficient emission of electrons from a tether system, as would any application requiring high currents and less potential drop across electron emitting components.

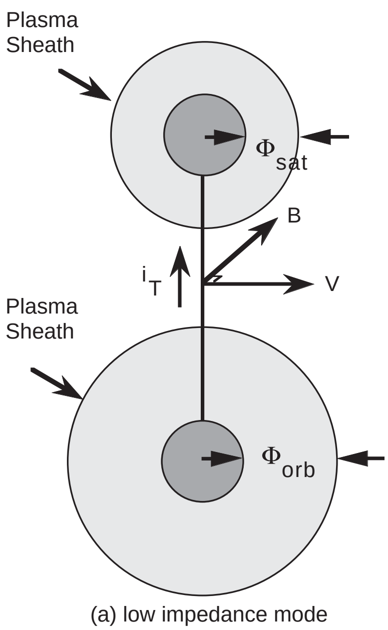

Figure 4. Schematic of an electrodynamic tether system flowing current.

Engineering Development Remaining

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. Primary amongst these developments is the need to explore optimal designs and material choices, since the vacuum of space is by no means "clean" or chemically inert. As a result, design geometries, materials, or surface coatings that protect devices in harsh environments may be needed; but this is not considered an impediment. SRI has previously explored and developed a variety of protective circuit features, tip geometries, materials, and coatings that would be applicable for space applications; but these would have to be revisited for particular applications and environments. Along similar lines, packaging and care of Spindt cathodes before they are put into operation is critical, as with any other microfabricated device. Spindt cathodes need to be kept clean and free of contaminants before use and ideally only exposed to the contaminants of a spacecraft environment at the time of use. This too is an issue already addressed and resolved for space applications of other technologies, such as optical systems, and so remains merely as an engineering consideration to be addressed for specific applications of Spindt cathodes.

Other issues that may require attention for specific applications include (1) Spindt cathode slow initial power-on procedures, which improve robustness and reliability by minimizing arcing caused by contaminants; (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); and finally (3) space qualification and testing to prove the viability of Spindt cathodes for space applications. None of these issues are considered impediments to the use of Spindt cathodes in space, but especially with regard to space qualification, nothing would be better than a test of sample devices in space to prove to the user communities that these devices can and do perform as advertized.

Conclusions

We find that the low impedance, low power, and low mass of Spindt cathode devices provides an excellent alternative to existing approaches for electron emission or gas ionization in many space applications. For example, without expendables associated with traditional plasma contactors or the mass and power requirements of plasma contactors and electron guns, Spindt cathodes are capable of producing multiamp electron currents. In this way, Spindt cathodes provide an enabling technology for the use of tether systems for orbit maneuvers and provide significant improvements and new capabilities for many electric propulsion technologies. Spindt cathodes are a dramatic improvement over existing electron emission technologies, and while there remain engineering and device optimization issues, Spindt cathode technology at SRI is ready for space application today.

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V. M. Agüero and R. C. Adamo, SRI International (MS-408-95), 333 Ravenswood Avenue, Menlo Park, CA 94025. (victor.aguero@sri.com and richard.adamo@sri.com)

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