Preliminary Study on Field Emitter Array Cathodes for Electrodymanic Tether Propulsion

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Abstract

A preliminary study on field emitter array cathodes was conducted aiming at applying for electrodymanic tether (EDT) propulsion systems. The EDT propulsion systems are assumed to use for active removal systems of post-mission spacecraft, which would otherwise become space debris. A survey on field emitter array cathode technology was conducted, and it showed that carbon nanotube (CNT) emitters are suitable to EDT application. Trial fabrications and evaluation tests of CNT emitters were conducted, which demonstrated a target emission current density of 10 mA/cm^2. It was found out that the most important technical issue for developing CNT emitters is to improve the performance against voltage breakdown between the emitter and the opposite electrode.

Introduction

In current space activities, most of the spacecraft are left in orbit after they finish the mission and become useless. The amount of such artificial objects left in space is increasing at very high rates. They will be a source of space debris unless their orbits are so low that they will fall into the earth atmosphere and burn out in a certain period of time. If space debris increases to such a level that cascading collisions among them will happen, it will cause a fatal impact on human space activities$^{1)}$.

The problem of space debris has been widely recognized, and some countermeasures are being taken or under investigation to mitigate the debris problem. One of them is de-orbiting the spacecraft after the end of mission and lowering it to the orbits in which it keeps orbiting only for a limited period, 25 years for example, and then naturally re-enters to the earth atmosphere.

The idea of this active removal of the spacecraft after the end of mission is very attractive to mitigate the debris problem, and recently we have started a research program of active removal systems for post-mission space systems$^{2)}$. It is very ambitious and requires new technologies. One of the most critical technologies is for orbit transfer. Though conventional propulsion systems can conduct de-orbiting for this purpose technically, it will cost a lot and bring economical difficulty. Propulsion systems with very high performance and cost-effectiveness are required to realize this concept.

Electrodymanic tether (EDT) systems are the most promising candidate. EDT produce thrust by using a force that is produced when running a current through a wire in the geomagnetic field. They need no or little consumables, which is the predominant feature in comparison with other propulsion systems. Moreover, in the application to orbit lowering, the electromotive force produced by the motion of the tether is effectively used to generate a drag force, and no external power source is required, in contrast to electric propulsion.

To form a current loop together with space plasmas, EDT systems need electron emitters at one end and electron collectors at the other end. There are some devices available for the electron emitters. Field emitter array cathodes (FEAC) are one of them, and very promising because of their simplicity and the features of no-consumable and low-power operation$^{3)}$. A lot of small cathodes are contained in FEAC. Each individual cathode emits an electron current of only micro-amp levels, but a high-density array of the cathodes can offer the possibility of current density in ten milli-amp per square centimeters or higher.

The focus of this paper is FEAC. FEAC are a new technology and have not been matured yet for space use. Thus, a feasibility study on FEAC was conducted as a first step. A survey was made to get the current status of this technology. Then, FEAC emitters were fabricated as a trial to reveal technical issues to be dealt with for the next step of the development.

Electrodynamic Tether

EDT Operation

Figure 1 shows a conceptual illustration of the debris de-orbiting system using EDT. In this system, an EDT system is attached to a post-mission satellite, which would become space debris if left in orbit. A drag force to the EDT lowers the orbit of the system. The force to the tether is produced by a Lorentz's force, which is induced by the interaction of a current

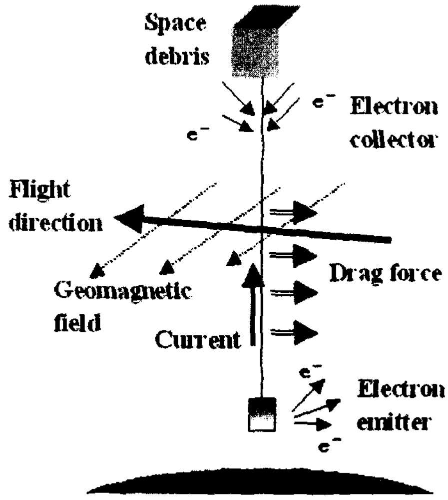


Fig. 1 Concept of the debris de-orbiting system using EDT.

through the tether wire and the geomagnetic field. A loop circuit is required to drive the current, and a part of the current loop is composed by the tether wire and the rest by surrounding space plasma. To complete the loop, the tether needs to collect electrons from the space plasma at one end, and to emit electrons at the other end. Ions in space plasma move much slowly than electrons, and thus we have to rely on electron currents to have electrical contacts with space plasma.

There are some devises proposed to collect electrons[4]. The simplest one is a bare tether, that is a simple conductive wire bare to space plasma. Owing to orbital motion of electrons around the wire, the wire can collect electrons from an effective area much wider than its physical surface. Alternative is a hollow cathode. It is a matured technology for the electron source in electric propulsion, but its function as an electron collector has not been fully understood yet.

There are also some devises proposed to emit electrons. A hollow cathode and FEAC are promising among them. Hollow cathodes are technically matured, already available, and thus suitable if we need early development of EDT systems. However, they have a disadvantage that they need consumables or working gas to operate, and thus valves and tanks for working gas management. This may make the EDT system heavy and complex.

The situation in FEAC is contrary. Electron emission systems can be constructed with simplicity using EDT if this technology is fully developed. So far FEAC technology development has made steady progress mainly in the field of display, but it has just started to use for EDT in space. This justifies the need for developing FEAC for EDT systems.

Environmental Conditions

The active debris removal systems assume to apply to post-mission satellites in low earth orbits, with an altitude range of 800 to 1400 km for example. De-orbiting down to 630 km is assumed, where the orbit life is as short as 25 years.

Environmental conditions in this attitude range set out requirements for the FEAC. Standard pressure at 600-km altitude is of the order of 10^{-7} Pa[5], and it has variations of one or two order of magnitude depending on solar activity[6]. The atmosphere contains atomic oxygen, and it may possibly oxidize the surfaces of the emitters, resulting in short lifetime. The flux of atomic oxygen is estimated at about 5 x 10^{21} atoms/cm^2/year at the ISS orbit (about 400-km altitude). Ions in space plasma may sputter the surfaces of the emitters. Plasma density is of the order of 10^{11} /m^3 at 600-km altitude[5].

Survey on FEAC

A survey was conducted on the current status of FEAC technology both for Spindt-type and carbon nanotube (CNT) emitters. Comparison was made in the view point of EDT application.

Spindt-type Emitters

As Spindt-type emitter materials, molybdenum and silicon are often used. Molybdenum emitters provide large emission current, but are chemically active. Silicon emitters have somewhat small emission current, but are not so much influenced by impurities.

Some problems in Spindt-type emitters are already revealed. Changes in the surface conditions and impurities on the surfaces can lower their current-emission capability. Thus, the operation pressure has to be an ultra-high vacuum of the order of 10^{-7} Pa or higher, and a special technique is required for cleaning the emitters. Voltage breakdown is another problem, and once isolation breakdown occurs, emitter elements are destroyed and no more recovery can be made.

CNT emitters

Carbon nanotubes have cylindrical structures formed with graphite sheets. There are two kinds of carbon nanotube; single-wall nanotubes (SWNT) and multi-wall nonotubes (MWNT). Graphite nanofibers (GNF) have layered cylindrical structures that are not hollow.

A survey was made of their field emission capability. Table 1 shows emission current per nanotube[7]. Emission current can be greatly increased by making the tips of nanotubes open with an oxidization process. Current emission capability per nanotube is as large as one μA. While decrease in emission current occurs about in 10 hours in SWNT, MWNT can maintain the emission current stably for longer than 1000 hours. Though various processes are available for CNT emitter production, they all provide almost the same

Table 1 Emission current per nanotube.

Configuration	Tip	Current per CNT
MWNT	Capped	0.5 – 3 nA
MWNT	Open	400 – 900 nA
SWNT		50 – 300 nA

Table 2 Characteristics of the emitter samples.

Sample	Configuration	Production	Size
A	MWNT	Thermal CVD	10 mm dia.
B	MWNT	Arc Discharge	9.5 mm dia.
C	GNF	Thermal CVD	10 mm dia.

maximum levels of emission current density of the order of 10 mA/cm^2. This is mainly because the present development of CNT emitters is for applying to displays, and thus emission requirements are not so high (less than 1 mA/cm^2).

There are some technical issues on CNT emitters. One of them is isolation breakdown. Breakdown voltage of CNT emitters is much lower than that of metal electrodes. Another is that the emission current levels are much lower than the values that are guessed from the emission capability per nanotube. This means that it may be possible to obtain much higher emission current if nanotube arrangements and characteristics are improved by developing technology in this field.

Comparison

In comparison with Spindt-type emitters, CNT emitters offer many advantages. They have lower threshold in field emission (1 to 2 kV/mm), are only slightly affected by surrounding gas conditions, and have longer lifetime. They cannot be destroyed by isolation breakdown, and are easy to fabricate.

A special emphasis should be placed on their operating pressure. While Spindt-type emitters need an ultra-high vacuum of about 10^{-7} Pa or higher for normal operation, CNT emitters can give normal current for longer than 1000 hours at operating pressure levels of the order of 10^{-3} Pa. This indicates that only CNT emitters will be applicable to EDT because EDT systems have to be operated in space at pressure levels of about 10^{-6} Pa. Practically, it is very difficult to keep the emitters installed in EDT in vacuum on the ground and during launch. Effects of atomic oxygen are a concerned problem, and it has to be examined experimentally. It is guessed that oxidization of CNT may produce gaseous CO_2 but will not cause sudden degradation, while metal electrodes will be easily oxidized to form an oxide layer on the surface, resulting in failure.

FEAC Development

Preliminary Fabrication

To reveal the field emission capability and technical issues of FEAC, test fabrications of FEAC were conducted, and current emission characteristics were obtained. A target of emission current density was set as 10 mA/cm^2, considering that a current level of an order of 1 A is required for the EDT of the proposed active debris removal system under study and assuming a reasonable size of the emitter to be about 10 cm square.

Three kinds of CNT emitter were fabricated, and Table 2 summarizes the characteristics of these emitter samples. Sample A was fabricated by remaking an emitter for a fluorescent tube into a test emitter. The original one had a metal-mesh grid over the emitter, but it was removed in the remaking. Sample B was fabricated from CNT powder processed with purification. The CNT powder was obtained from a cathode in arc-discharge equipment, and the purification process consisted of grinding in a mortar, ultrasonic dispersion in ethanol, and thermal treatment. The emitter was made by fixing the powder on a copper electrode with conductive adhesive. Sample C was made on an invar substrate plate with thermal CVD process. Its form is not CNT but GNF.

Figures 2 and 3 show photographs and SEM images of the samples, respectively.

Evaluation Test

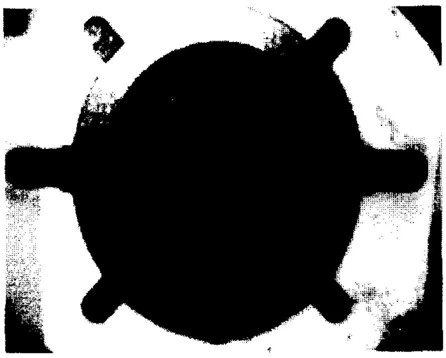
Evaluation tests were conducted to obtain emission characteristics of the samples. Figure 4 shows a schematic of the test apparatus and vacuum chamber for the evaluation tests. The chamber was evacuated with a turbomolecular pump, and the tests were conducted at 3 x 10^{-3} Pa.

In the test chamber, a flat anode was arranged parallel to the sample with a gap of 2 mm. The anode was made of a 35-mm diameter glass disc that was evaporation-coated with indium tin oxide. The anode diameter is much larger than the emitter size, and the emitter is surrounded by an area without CNT. This arrangement suggests that the electric field is uniform over the emitter in the strength and direction. The emission current was measured as a voltage applying to a 10-kΩ shunt resister.

Test Results

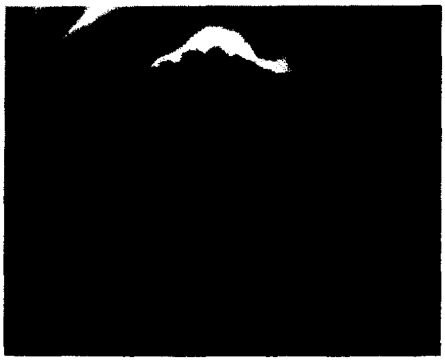
Figure 5 shows an electron emission characteristic of Sample A. It has a threshold for emission at 1.5 kV/mm, and a current density of 0.8 mA/cm^2 was obtained at an electric field of 3 kV/mm. Figure 6 is a photograph of the luminous sample during the test. The luminosity distribution is not perfect in uniformity and has dotted luminous spots. The test was restricted within the electric field range up to 3 kV/mm, above which frequent isolation breakdown occurred.

Figure 7 shows an electron emission characteristic of Sample B. It has a threshold for emission at 1.2



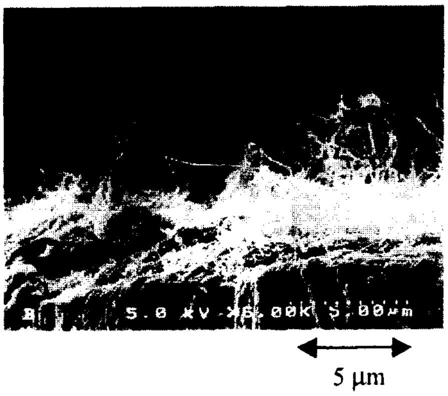
(a) Sample A

(b) Sample B

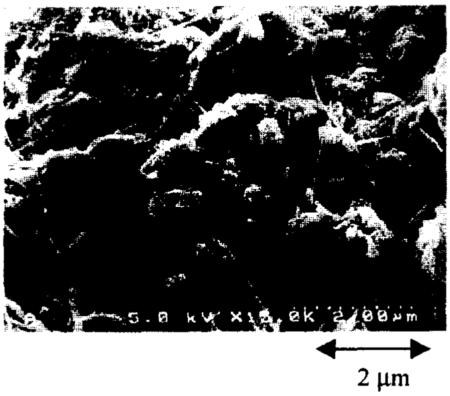


(c) Sample C

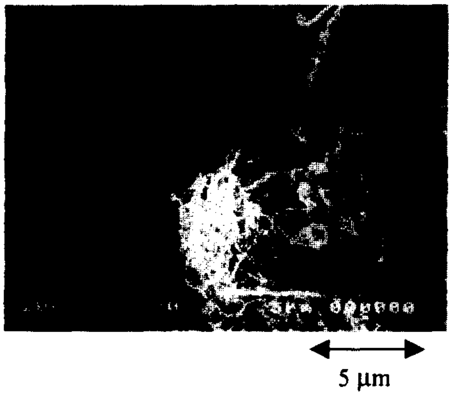
Fig. 2 Photographs of the samples.



(a) Sample A



(b) Sample B



(c) Sample C

Fig. 3 SEM images of the samples.

kV/mm, and a current density of 10 mA/cm^2 was obtained at an electric field of 2 kV/mm. Application of higher electric fields caused voltage breakdown, and thus the test was stopped at this electric field. Figure 8 is a photograph of Sample B, which shows dotted luminous spots as in Sample A.

Figure 9 shows an electron emission characteristic of Sample C. It has a threshold for emission at 1.2 kV/mm, and a current density of 2.7 mA/cm^2 was obtained at an electric field of 1.7 kV/mm. The test range was up to 2 kV/mm, above which isolation breakdown also occurred.

Sample B achieved the target emission current of 10 mA/cm^2. Sample C had a problem of low breakdown voltage, and did not achieve the target current density, but its voltage-current characteristic is almost the same as that of Sample B. Sample A had an emission-current density level of an order-of-magnitude

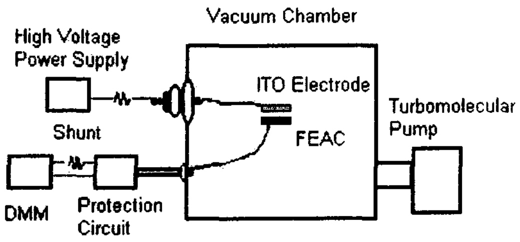


Fig. 4 Test apparatus and vacuum chamber for the evaluation tests.

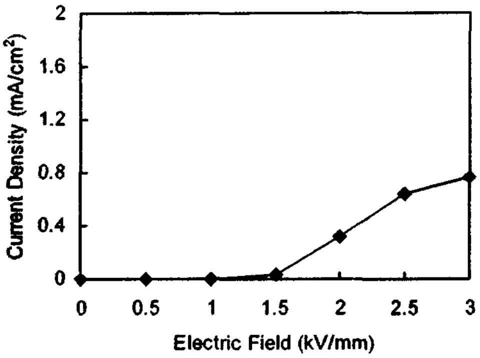


Fig. 5 Electron emission characteristic of Sample A.

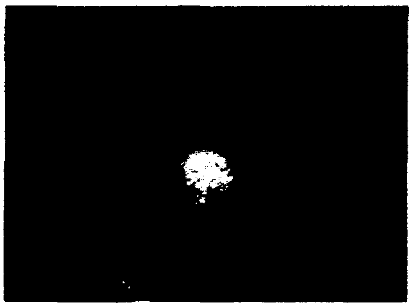


Fig. 6 Sample A in the test.

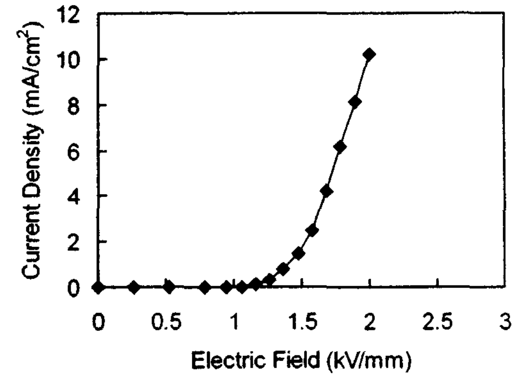


Fig. 7 Electron emission characteristic of Sample B.

Fig. 8 Sample B in the test.

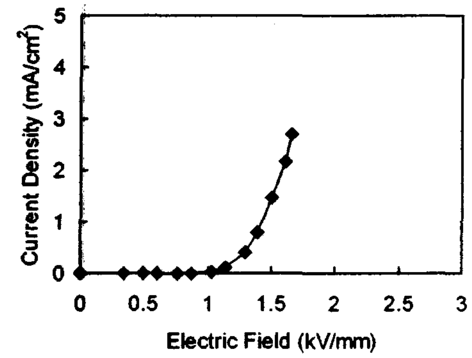


Fig. 9 Electron emission characteristic of Sample C.

smaller than the other samples. It has a grid-pattern emitter and thus a smaller effective area than the other samples. However, the current density level in Sample A is too low to explain it from the small effective emitter area. Potential emission capability of the original emitter for Sample A may be much higher than the obtained data. It is guessed that the emission capability was decreased during the fabrication process to a fluorescent tube.

These test results proved that the most important technical issue to work on about CNT emitters is in voltage breakdown between the emitter and the opposite electrode. The emission current was not saturated with the increase in the applied electric field. This means that higher current can be obtained by improving isolation against the voltage breakdown.

The luminous patterns in these samples were all dotted, and, considering the area covered with CNT, this suggests that not all the emitters contribute to the emission. This means that it is possible to obtain larger levels of electron emission by taking better control of the arrangement and characteristics of CNT. This is another technical issue for CNT emitters to work on.

Conclusion

The survey on current FEAC technology indicated that CNT emitters are suitable to EDT application. The trial fabrications and evaluation tests of CNT emitters demonstrated the target emission current density of 10 mA/cm^2. It was found out that the most important technical issue for further development of CNT emitters is to improve the performance against voltage breakdown between the emitter and the opposite electrode.

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