Investigation of Endurance Performance of Carbon Nanotube Cathodes

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The Aerospace Research and Development Directorate of the Japan Aerospace Exploration Agency (JAXA) is considering a demonstration of electrodynamic tether (EDT) systems in low Earth orbit (LEO). Carbon nanotubes (CNTs) have some advantages as electron sources compared to conventional Spindt type emitters, and so are expected to be useful in EDT systems. Experiments to investigate the durability of CNT cathodes in a space environment had been conducted in a diode mode, but it was found that electron extraction tests, in which the cathode with a gate electrode is used, are necessary to evaluate the endurance of CNTs more accurately. In this paper, we conducted long duration operating tests of a cathode with a gate. It was found that there was almost no change in cathode performance at current densities below 100 A/m² even after the cathode was operated for over 500 hours in the high vacuum environment.

Key Words: Carbon Nanotubes, Field Emitters, Electrodynamic Tether, LEO Environment

Nomenclature

E	:electric field
r_{tip}	:radius of curvature of a tip
d	:electrode separation
V	:interelectrode voltage
J	:current density
e	:electron charge
h	:Plank's constant
ϕ	:work function
m_e	:electron mass

1. Introduction

The excellent field emitter properties of carbon nanotubes (CNTs) are expected to make them useful as electron emitters in electrodynamic tether (EDT) systems. The Aerospace Research and Development Directorate of the Japan Aerospace Exploration Agency (JAXA) has been conducting research and development of CNT cathodes for EDT systems^{1,2)}.

An EDT system comprises a conductive tether with plasma contactors attached to each end. Electrons are collected from the ambient plasma at one end and are emitted at the other, forming a closed circuit through the tether and the ambient plasma. The interaction between the current flowing through the tether and the geomagnetic field generates a Lorentz force on the tether. Three electron emitter technologies are usually considered for space applications: hollow cathode, thermionic cathode and field emission cathode (FEC). It is believed that FECs are the most suitable for EDT systems because they have a very simple structure and are expected to operate with low power. A CNT cathode is a type of FEC.

Compared to Spindt type cathodes which have been conventionally studied as FECs, CNT cathodes are

expected to have high efficiency, stable operation, and long life in the low earth orbit (LEO) atomic oxygen and plasma environment. However, their operational characteristics and the degradation mechanism of CNT cathodes in the space environment have not been proven so far. In this study, long duration operational tests of CNT cathodes were conducted at various current densities.

2. Variety and Structures of CNTs

Carbon nanotubes are roughly classified into single walled CNTs (SWNTs) and multiwalled CNTs (MWNTs). An SWNT is a graphite sheet rolled into a cylinder of a few micrometers in length and a few nanometers in diameter. An MWNT consists of several such cylinders nested inside each other^{3,4)}. An SWNT has a higher emission efficiency than an MWNT because of its sharpness. On the other hand, the MWNT's multiple layers give it greater mechanical strength and so it is expected that MWNTs will have a longer life.

3. Field Emission Cathodes

3.1. Fundamentals of FECs

Figure 1 shows (a) a typical example of a Spindt type cathode, which consists of a gate electrode and an array of cone type metallic emitters, and (b) a single element of the cathode. Generally, the gate is a metal film with apertures over each emitter.

FECs are electron sources using the phenomenon of field emission of electrons from the surface of a solid material. The electric field concentrates at the emitter tips and when a voltage is applied between the gate and the emitters, electrons are emitted by the tunnel effect, as shown in Fig. 1(b).

Fig. 1. (a) Schematic of Spindt type cathode, (b) a single element of the cathode.

Here, we briefly introduce the fundamentals of field emission using the model shown in Fig. 2, in which a single emitter with a parabolic shaped tip faces a simple disk anode.

Fig. 2. Model of a single parabolic shaped emitter facing an anode.

The electric field E obtained by applying a voltage between the emitter and the anode can be written as follows ⁵⁾:

$$E = \frac{2V}{r_{tip} \ln(2d/r_{tip})} \quad (1)$$

where r_{tip} is the radius of curvature of the tip, d is the electrode separation, and V is the interelectrode voltage. The current density J obtained by field emission is given by the Fowler-Nordheim (F-N) equation in Eq. (2) ⁵⁾

$$J = \frac{e^3 E^3}{8\pi h \phi} \exp\left(-\frac{8\pi\sqrt{2m_e}}{3heE} \phi^{3/2}\right) \quad (2)$$

where e is the electron charge, h is Planck's constant, ϕ is the work function of the emitter, and m_e is the electron mass. From Eq. (1) and (2), it can be understood that the electron emission capability strongly depends on the sharpness of the radius of curvature of the tip and the work function of the emitter.

3.2. Advantages and Disadvantages of FECs

For Spindt type cathodes, it is possible to arrange the

emitter array uniformly to obtain a homogeneous current distribution, as shown in Fig. 1(a). However, the array's performance is degraded by two effects. If ambient ions or ions generated between the electrodes sputter the tips, the resulting increase in tip radius reduces the geometrically enhanced electric field at the tips and field emission capability degrades rapidly. Also, the work function increases due to the formation of an oxide film on the emitter surface due to reaction with atomic oxygen ⁶⁾. From Eq. (2), an increase in the work function means a greater voltage is needed to extract electrons, which causes a degradation of cathode performance.

In contrast, CNT cathodes have the drawback of a non-uniform current distribution because it is difficult to align each nanotube uniformly. On the other hand, CNTs have high mechanical strength and are highly resistant to ion bombardment: even though ion bombardment abrades the nanotube tips, it is expected that tip sharpness is retained because of the tubular shape of the CNT. Moreover, CNTs are expected to be more durable than Spindt type emitters because their surfaces are believed to be chemically stable and inert. However, their tolerance to atomic oxygen and oxygen plasma in LEO has not been sufficiently verified at the present time.

4. Review of Previous Works ⁷⁾

JAXA has conducted experiments to evaluate the environmental durability of CNT cathodes. Since the objective was merely to evaluate durability, the experiments were conducted in a diode mode, which consists of a CNT emitter and an anode without a gate electrode.

First, operating tests were performed in various gaseous atmospheres to investigate the influence of gas species. While ions generated by electron bombardment in the vicinity of the cathode were found to have almost no effect on cathode performance, oxygen caused irrecoverable degradation. We believe that the chemisorption of oxygen on the CNT surface increases the work function and so increases the operating voltage.

Next, endurance tests were conducted in an oxygen environment to study cathode degradation characteristics. The results showed a gradual degradation at emission current densities below 100 A/m², but in the case of 260 A/m², the operating voltage rose rapidly. It was supposed that when current density increases to a certain level, the temperature of the CNT becomes high enough to cause chemisorption of oxygen on its surface and evaporation of the CNT itself due to oxidation. In some cases, the cathode suddenly lost its electron emission capability. We supposed that multiple micro-discharges occurred between the anode and emitter, causing CNTs to be removed from the emitter surface. Factors causing micro-discharge were considered to be gases emitted from the anode and CNTs and insufficient inter-electrode separation.

From these results, it was supposed that CNT cathode

degradation and failure was closely related to heat radiation and outgassing from the anode. Consequently, it was suggested that endurance tests should be performed in an electron extraction condition, which is equivalent to practical emitter operation. These experiments are the focus of this paper.

5. Experimental Apparatus

Figure 3 shows the schematic of the experimental setup and the configuration of the CNT cathode used in the new experiments. To simulate practical operating conditions and remove anode influences, we used a cathode consisting of a gate, a mask and a CNT emitter, and covered these with a shield case. Electrons are extracted by the gate and collected by an anode placed opposite to the cathode body. The mask on the emitter surface plays an important role in preventing electrons from flowing into the gate¹⁾.

Fig. 3. Schematic of the experimental setups.

Figure 4 shows (a) the appearance of the cathode and (b) a close-up view of the double slit of the mask and gate. Figure 4(b) shows that the gate and mask have overlapping slit apertures. The physical characteristics of the mask, gate and anode are summarized in Table 1.

The current to the emitter, gate, mask, and case are measured across four 5 kΩ shunt resistances using analog input boards. The bias voltages of the emitter, gate, and anode are controlled automatically by analog output boards.

Fig. 4. (a) Appearance of the cathode, (b) close-up view of the double slit of the mask and gate.

Table 1. Mask, gate and anode physical characteristics.

	Mask	Gate	Anode
Material	Mo	Mo	SUS
Thickness[mm]	0.05	0.1	3.0
Slit width[mm]	0.4	0.4	
Rib width[mm]	0.1	0.1	

Figure 5 shows detail of a CNT emitter. The emitter is a stainless substrate coated with a CNT film of numerous MWNTs grown by arc discharge. The CNTs are a few tens of micrometers in height and a few nanometers in diameters. Figure 6 shows a SEM image of the CNT film bonded to the substrate. As can be seen, the CNTs used in our study are complexly intertwined.

Fig. 5. Detail of a CNT emitter.

Fig. 6. SEM image of a CNT emitter surface.

The cathode was set in vacuum chamber which could be evacuated to a pressure on the order of 10^{-6} Pa. Figure 7 shows typical current-voltage characteristics of the CNT cathode obtained at a chamber pressure of approximately 1.5×10^{-5} Pa. The emitter current indicates the total current emitted from CNTs and is equivalent to the sum of the current intercepted by the gate, case and the anode current. Current density is calculated by dividing each current by the surface area of the CNT emitter including the area covered by the mask. In this experiment, the gate and anode voltages were fixed at 0V and 100V, respectively, and the emitter bias voltage was increased by 1 V per second until the emission current density reached 70 A/m^2 . The instantaneous values of current and emitter potential were recorded at 10-second intervals. The emission current measurement error is less than 4%, which includes the error of measurement systems and the fluctuating characteristics of the emission current. Figure 7 shows that the electron current flow to the gate is

negligible. This high extraction efficiency is attributable to the beam converging effect by the mask on the emitter.

Fig. 7. Current-voltage characteristics of a CNT cathode with a gate.

6. Results and Discussion

Two long duration operating experiments were conducted in high-vacuum conditions at various current densities to investigate the operating characteristics of a CNT cathode with a gate. Unless noted otherwise, current density refers to emitter current. Electron extraction voltage indicates the emitter-gate voltage.

In the first experiment, the current density was varied between 50 and 100 A/m^2 and the electron extraction voltage to sustain each current density was measured. The test conditions are summarized in Table 2. A single emitter sample was used in all the cases. The current density was first set at 50 A/m^2 for 170 hours, then was controlled at 75 A/m^2 for 65 hours, 50 A/m^2 for 70 hours, 75 A/m^2 for 20 hours, 100 A/m^2 for 160 hours, and finally 50 A/m^2 for 30 hours by turns.

Fig. 8. Historical logs of current density (top) and emitter-gate voltage (bottom).

Table 2. Conditions of the first experiment.

Pressure	$8.8 \times 10^{-6} - 1.2 \times 10^{-5}$ Pa
Emitter-gate distance	0.4 mm
Emitter-anode distance	15 mm
Emitter potential	-100 V
Gate potential	Positive bias
Anode potential	100 V
Current density	50, 75, 100 A/m ²

Figure 8 shows the historical logs of the emission current and the emitter-gate voltage needed to maintain each current density. It is seen that the extraction voltage becomes stable within a few tens of hours after setting each current density of 50, 75, and 100 A/m².

After the CNT cathode had been operated for about 160 hours at 100 A/m², the current density was set to 50 A/m². A few tens of hours later, the electron extraction voltage decreased rapidly and recovered to a level comparable with the voltage when the operating test was started at 50 A/m². From this result, it is assumed that even though the cathode was operated for a few hundred hours at below 100 A/m², there was almost no effect on cathode performance due to CNT degradation in the high vacuum environment. Consequently, the elevation of the extraction voltage when current density was changed from 50 to 75 A/m² is a transitional phenomenon and is not attributable to CNT degradation.

In the second experiment, the current density was first maintained at 25 A/m². When the emitter-gate voltage had stabilized, 25 A/m² was added to the initial emission current. This process was repeated until the current

density reached 100 A/m². Table 3 shows the experiment conditions. A single emitter sample was used in the experiment.

Table 3. Conditions of the second experiment.

Pressure	$2.9 \times 10^{-6} - 1.2 \times 10^{-5}$ Pa
Emitter-gate distance	0.3 mm
Emitter-anode distance	10 mm
Emitter potential	Negative bias
Gate potential	0 V
Anode potential	475 V
Current density	25, 50, 75, 100 A/m ²

Figure 9 shows the historical logs of the emitter-gate voltage at each current density. In this figure, the time zero reference is when the cathode started to operate at each current density. The figure indicates that the extraction voltages tended to be almost stable throughout operation at all current conditions. This result agrees with that of the first experiment.

Before performing these two experiments, we had expected that the increases in voltage and the time required until the voltages stabilized would be proportional to the magnitude of the current density. However, no such tendency can be observed in Fig. 9. It seems that cathode performance in a high vacuum does not depend on the magnitude of the current density if the current density is below a certain level (100 A/m² in this case). Variation of surface conditions between different CNT emitter samples seems to be the more dominant factor affecting emission characteristics.

Further investigation is required to understand the

Fig. 9. Time-dependent variation of emitter-gate voltage at each current density.

voltage variations seen in Fig. 9 in detail. We are planning approaches such as chemical analysis of the CNT emitter surface before and after operation, and *in situ* measurement of CNT temperature.

7. Conclusion

Long duration cathode operation tests were conducted using a cathode with a gate electrode to evaluate cathode endurance in conditions similar to those of operational electron extraction. Time-dependent characteristics of electron extraction voltages at various current densities were obtained. Almost no degradation of cathode performance was observed after a few hundred hours of operation in high vacuum conditions at current densities below 100 A/m².

We are now trying to simulate the LEO environment in which atomic oxygen is dominant, and to investigate the durability of CNT cathodes in an oxygen environment.

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