Carbon Nanotube Chip Applications in Electric Propulsion Systems for Nanosatellites

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Carbon nanotube chips have the potential to greatly improve the propulsion system for nanosatellites orbiting Earth. Because of the small size of nanosatellites, their propulsion systems operate nominally at lower power levels to maintain attitude during their life cycle compared to their larger counterparts. The use of carbon nanotubes as an electron emission source offers an alternative to traditional electric propulsion systems that utilize thermionic emission and excess propellant to neutralize the thruster ion beam. This method requires applied heat to the cathode and a system to carry and deliver the propellant while in space in order to complete neutralization. Carbon nanotube cathodes offer an alternative to these methods without the use of propellant or the addition of heat. The required hardware for the implementation of carbon nanotube chips has a smaller footprint on the spacecraft compared to established neutralization methods, which is key when working with nanosatellites. While carbon nanotube cathodes exist commercially, the design is not optimized for small satellite applications. An introduction to the structure and operation of carbon nanotube chips will lead into a discussion of several experiments previously conducted for in-space applications of carbon nanotube cathodes. Recommendations for design changes and future work with carbon nanotube experimentation are proposed, including an experimental setup and vacuum chamber facility details.

I. Introduction

Over the last 40 years, electric propulsion has emerged as one of the leading propulsion methods for in-space systems. However, it is also one of the fields undergoing the most development moving into a new age of commercial space exploration. With more and more systems entering orbit around Earth, the need for efficient and cost-effective propulsion and maneuvering systems is growing, especially for small satellite applications. Field emission cathodes (FECs) offer a promising solution to propellantless neutralization methods, especially for application in nanosatellites with long lifetimes. The term "nanosatellite" loosely refers to a small satellite weighing less than 10 kilograms (22 pounds) [1]. The challenges involved in designing a long-term nanosatellite mission include power storage capacity, onboard storage area, and weight of onboard systems [1], therefore limiting the hardware required for the propulsion system can improve the performance of the satellite. For this size satellite, a low-power thruster is often used. This configuration requires less emission current to neutralize the ion plume compared to the more substantial electric propulsion systems used in larger satellites. For nanosatellite applications, field emission cathodes are a promising option because of their lack of propellant use and higher energy efficiency. Within the category of field emission cathodes, carbon nanotubes (CNTs) offer an interesting option because of their compact nature and the resistance to wear and tear due to ion sputtering from the ion thruster [2]. The following sections introduce the carbon nanotube structure, present previous field emissions experimentation with carbon nanotubes for space applications, and detail future investigations into carbon nanotube cathode characteristics.

II. Carbon Nanotube Chips and Application in Space Propulsion

Carbon nanotubes are microscopically small structures made up of carbon atoms connected by carbon-carbon bonds [3]. This configuration is just one of the many formations carbon can take on, and is very strong because of the carbon bonds in the structure [3]. Figure 1 shows the microscopic structure of a single carbon nanotube.

These structures can be grown in densely packed clusters on silicone wafer chips to form a carbon nanotube chip. One concern with this mode of manufacturing it the possibility of electrical shorting between the individual CNTs in the clusters, which will affect the operation of the field emissions [4]. These CNT chips can then be used for a variety of

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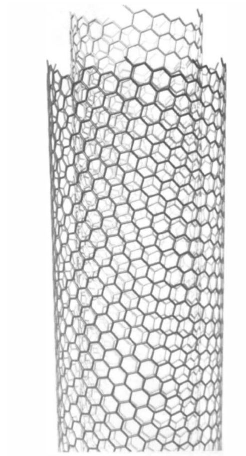

Fig. 1 Carbon nanotube structure [3].

applications, from screen displays to power amplifiers. This paper will focus on the applications in field emissions for ion neutralization in electric propulsion systems.

In ion thruster electric propulsion systems, the source of thrust comes from ionizing a noble gas and accelerating the ions through an electric field, then neutralizing them at the exit of the thruster using a cathode [5]. The cathode provides a field of emitted electrons to neutralize the plume. Oftentimes the thruster uses a propellant such as xenon to provide a source of ions [5]. Many variations of these cathodes exist, and they often require heat to emit electrons or require more of the propellant used in the thruster [2]. By biasing the carbon nanotubes with enough voltage potential, the carbon atoms will actually emit electrons from the structure [3]. These emitted cause an electron emission field that can be used in the cathode to neutralize ions in the ion beam of an electric propulsion system. Using CNTs as a source of emitted electrons does not require increased temperature or use of propellant [4], which makes them an ideal candidate for a cathode. However, the current from the emitted electrons has proven to be smaller compared to other cathode options, so the application of CNTs should be reserved for smaller, low-power electric propulsion systems such as those on nanosatellites.

The experiment configuration for electron field emission with carbon nanotube chips typically takes two forms: a diode configuration or a triode configuration [4]. A diode configuration has a cathode attached to the carbon nanotube clusters on the silicone wafer and an anode placed at a standoff distance above the carbon nanotubes. A triode configuration is similar to the diode configuration but with the addition of a gate to the electrical setup. The gate is used to drive electron emission and improves the efficiency of the device [4]. Figure 2 shows a schematic of the triode setup.

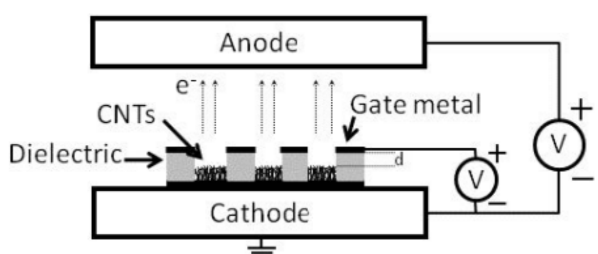

Fig. 2 Triode carbon nanotube testing setup [4].

Experimentation with carbon nanotube field emissions is conducted at high vacuum because of the small amount of electrons emitted from the collection of carbon nanotubes [4]. Without the vacuum, the atmosphere impacts the current readings and whatever measurements taken are insignificant.

III. Overview of Current Technologies

Ever since the first observation of field emission from carbon nanotubes in 1994 [4], scientists, engineers, and physicists have conducted testing for a variety of applications. The following section introduces several key experiments that will inform future efforts in the study of carbon nanotube field emissions for use in electric propulsion systems. The goal of this future work will be to improve upon the testing setup and configuration of the carbon nanotube chips and to validate their use as an emission source for neutralization of electric thrusters.

Testing conducted at the NASA Jet Propulsion Laboratory at the turn of the century concluded that field emission cathodes are an effective method for neutralizing the charges in an ion thruster [6]. The authors concluded that the cathode was successful and even improved the performance of the thruster compared to traditional thermionic neutralization methods in terms of propellant use and emission current [6]. The authors indicate that carbon nanotube cathodes are a good candidate for the cathode in field emission electric propulsion thrusters, but they do have some drawbacks such as high gate currents which cause a decrease in efficiency and higher sensitivity to the surrounding environment [6]. Finding innovative ways to decrease the current at the gate and increasing the durability of the carbon nanotube cathodes during operation are considerations made in the following sections.

In 2008, testing of carbon nanotube cathodes was also conducted at the Georgia Institute of Technology High-Power Electric Propulsion Laboratory. The authors discuss the requirements of the cathode for application in low-power electric propulsion devices, such as a 1500 hour lifetime and a required current supply of 0.1-1.0 mA [7]. During the experiments, the CNT cathodes were tested for a maximum duration of 50 hours of at pressures below $5x10^{-5}$ Torr [7]. Further experimentation is proposed for testing at a higher vacuum level for a longer duration to test durability and lifetime.

In 2019, researchers at the Kyushu University in Japan in conjunction with the Japan Aerospace Exploration Agency conducted testing of carbon nanotube cathodes with ion thrusters. This testing involved running a carbon nanotube cathode with an ion thruster with xenon as the propellant [8]. The gate voltage against emitted potential was varied between 0-500 V, which gave a large range of data to interpret results from [8]. The authors assert that this is the first time such an experiment has been successful, and shows how new these methods are to the field of electric propulsion. The success of these experiments will inform the expected results of future work.

Table 1 shows compiled data from the chosen experiments for review. This list is not exhaustive, but gives an idea of the expected values for voltage, current, and chamber pressure when testing carbon nanotubes. This data will be used to inform future experimentation addressed in the following sections.

Table 1 Table of applied voltages, currents, and chamber pressures for reviewed works.

Source	Applied Voltage	Observed Current	Chamber Pressure
[2]	300 V	2 mA	7.5 x 10^{-7} Torr
[9]	300 V	9 mA	NA
[6]	380 V	1.3 mA	NA
[10]	380 V	2.1 mA	NA
[7]	550 V	0.51 mA/cm^2	3 x 10^{-5} Torr
[8]	500 V	20 mA	7.5 x 10^{-7} Torr

As seen in Table 1, there is variation in the emission current and applied voltage, depending on the conditions of the experiment, the materials used, and the configuration of the experimental setup. Because of the small amount of current produced by the emission of electrons from the CNTs, any variation in test setup or any improvements made to the configuration can significantly impact the results of the experiment. Experimental results can vary based on chamber pressure, applied voltage, anode distance from the cathode or gate, and cathode distance from the ion beam (in experiments with a thruster included). Future work might involve optimizing some of these parameters to obtain the most efficient cathode for ion thrusters. Many of the mentioned papers identify a trade off between propellant use and power consumption for the carbon nanotube cathode [7] [8].

IV. Future Investigations

Current efforts are focused towards constructing an operational vacuum chamber for testing of new carbon nanotube chips. Figure 3 shows the vacuum chamber currently undergoing modifications for use in experimental testing anticipated to begin in March 2023. The facility is located at the Georgia Tech Research Institute, an affiliate of the Georgia Institute of Technology.

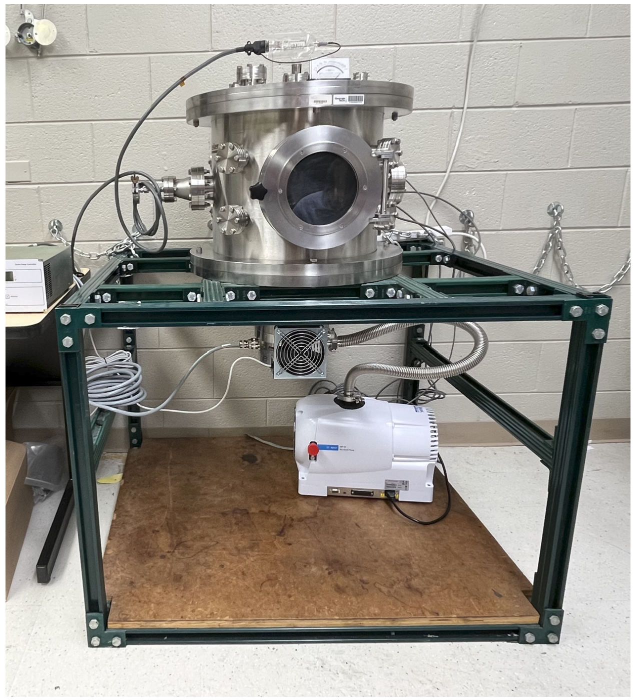

Fig. 3 Vacuum test chamber at the Georgia Tech Research Institute.

Testing of carbon nanotube emission is not possible at atmospheric conditions because of the low current produced by the carbon nanotubes [4]. In order to get meaningful results, the vacuum test chamber must reach a pressure of at least 10^{-7} Torr [7]. The measurement metrics of interest for carbon nanotube chip experiments are the current at the anode, the current at the gate, and the voltage applied to the test setup. As seen in Figures 4 and 5, the experimental setup will be in a triode configuration with a cathode, an anode, and a gate. A voltage difference will be applied to the cathode in order to emit electrons.

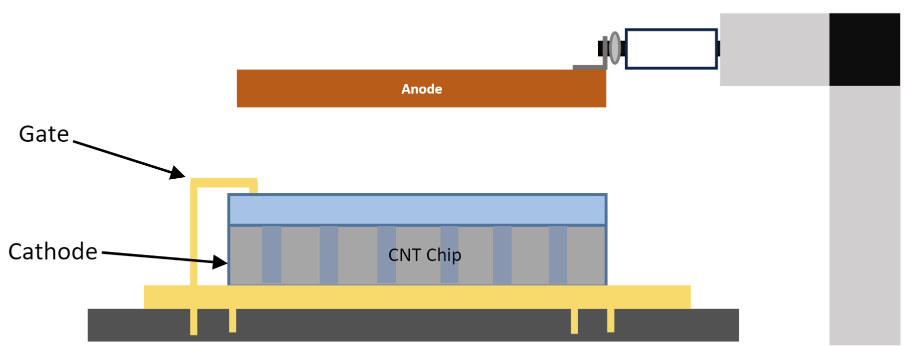

Fig. 4 Carbon nanotube chip testing electrical setup.

In order to decrease the wait time for testing due to custom ordered or machined components, a setup using commercially available components with short lead times was conceived. Figure 5 shows this configuration. A stainless steel, flat-nose clip will be used to secure the CNT chip in place. Adhesive PTFE film will be used to electrically isolate

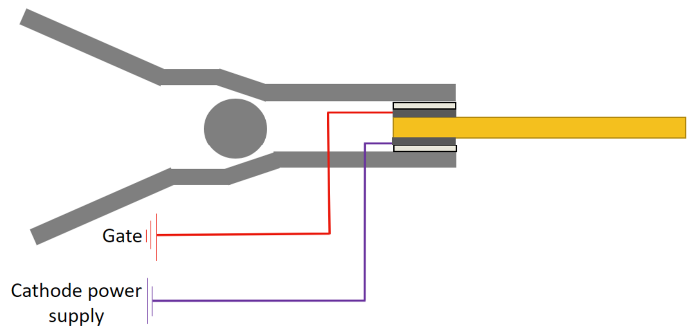

Fig. 5 Flat-nose clamp experimental setup with PTFE insulation.

the CNT chip from the clip. A flat plate connected to a wire will be clamped to each side of the chip to apply voltage and measure current. The top connection will be the gate voltage and the bottom connection will be the cathode of the setup. The anode configuration will still be the same as in Figure 4 in order to measure the current caused by the emitted electrons. Testing with different applied voltages and anode spacing will be conducted, along with shorting tests to ensure that the CNTs are not shorted with eachother.

V. Conclusion

Carbon nanotube chips show great promise in the future of in-space electric propulsion, especially for nanosatellite applications. For application of carbon nanotube field emission cathodes in flight systems, several design considerations must be made. In general, low out-gassing materials such as stainless steel, PTFE, boron nitride, and teflon are prefered materials for cathode construction and operation [5]. In addition, high voltage values are required to cause electron emission from the carbon nanotube chips [3]. This voltage will cause high temperatures in the hardware, so materials with a high heat resistance are required for long-term operation of the cathode.

Future work in the field should focus on optimizing the electron emission of the CNTs and improving the durability of the systems. Future work in this field should include long-duration, maximum-power tests and extended tests in the ion beam environment. Additional development and testing is needed to ensure the chips do not degrade over time or from exposure in the ion beam [4] [7]. Weak points in the current carbon nanotube cathode designs include lifetime testing and degradation of materials, especially when exposed to the in-space environment and the ion beam of the thruster. Further experimentation is needed surrounding the efficacy of the carbon nanotube chip propulsion technologies and their in-space applications. While current data suggests that this method of electron emission promises a more efficient ion neutralization method for ion thrusters, the lifetime and durability of these high-efficiency systems has still gone untested for extended missions.

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