CNT-based cold electron source for space applications on nanosatellites.

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Abstract: The orbit control of nanosatellites is of strong interest for educational purposes, research as well as industrial space missions. The recently developed highly miniaturized field emission electric propulsion system, called NanoFEEP enables mission extensions and orbit alteration manoeuvers of CubeSats. Since the momentum of the emitted ions in the µA-range generates a µN-thrust, an electron source is needed to prevent and neutralize the spacecraft charging. Therefore, a highly miniaturized neutralizer with a chip size of only 8x8mm^2 with performance data that corresponds to the strong power limitations of CubeSats is developed. The neutralizer is based on the technology of cold electron field emitters with an intense electrical field enhancement due to the application of Carbon Nanotubes (CNT). The simple electron source configuration consists of an emitter-chip, a mask electrode, and an extractor electrode. With the extractor-mask configuration, the transmittance leads to high values of about 70 to 85%. For the performance measurements, a triode arrangement is established with only one DC electrical potential of 500V to 3kV applied to the CNT-Chip, while the extractor and the anode (collector) are on ground potential. Various CNT substrates such as vertical aligned (VA)-CNTs on silicon, VACNTs on carbon fleece and CNT-buckypaper provide an intense electrical field enhancement and are considered and compared for the neutralizer implementation in terms of emission characteristics and stability. Long- term experiments up to 500h continuous operation present the emission stability and the slight degradation of the CNTs. The CNT-emitter is used as a neutralizer for the NanoFEEP thrusters on UWE4 satellite and further applications towards a CubeSat tether mission is under development. This paper will present the development of the electron source from the experimental setup to the final integration into the CubeSat.

I. Introduction

Nanosatellites are of high demand for educational purposes and industrial space missions. Recently, the developed highly miniaturized field emission propulsion system, called NanoFEEP enables orbit control, orbit alteration maneuvers and mission lifetime extensions to CubeSats [1]. The propulsion system contains three major elements. The thruster itself that generates a µN-thrust by the momentum of field emitted metal ions, a power-processing unit to create the needed high voltage and the cold electron field emitter that prevents spacecraft charging. The physical principle of field emission of electrons is selected due to its simplicity, the high degree of miniaturization capability, the absence of any propellant/ expellant or heater and the suffice of only on DC power supply. [1] The electron field emitter is already in use together with the NanoFEEP propulsion system on board of the UWE4 satellite of the University Würzburg, which was launched in December 2018 and is still operating as of today (September 2019). [2] Furthermore, future applications as a stand-alone cold electron source for space tether missions are under development. [3, 4]

In this paper, the development of the miniaturized neutralizer is described. At first, the design and experimental data of the early prototyping setup to review various emitter materials and configurations is presented. Afterwards the design and performance as well as the high current limit of the neutralizer is discussed.

II. Development of a cold electron field emission source

Electron field emission sources have only two central elements: the emitter and an extractor electrode, which are separated by an electrical isolator. To enable the dislocation and absorption of electrons from the emitter materials surface, a high electric field is needed. Therefore, vertically aligned multi-walled carbon nanotubes (VA-MWCNTs) are used. Carbon nanotubes are a novel material that was grown by chemical vapor deposition and consist of multiple concentric tubes of arranged single-layer carbon atoms. The nano-material is chemically inert, insensitive to ambient pressure and contaminations, is highly electrically and thermally conductive, has high mechanical strength and a relatively low work function in the order of metals. [5] This unique combination of physical, chemical and mechanical properties leads to a wide spectrum of applications in future space missions as ESD coatings, thermal blankets, high strength composite materials, sensors, and others [6] [7]. In addition and of high interest when applied as electron field emitters, the CNTs provides an intense electric field enhancement due to their high aspect ratio (ratio between length and diameter) to reduce the extracting voltage and therefore reduce the power consumption.

A. Considered emission materials

Various nano-materials are surveyed by their applicability as electron field emitter for the miniaturized neutralizer. Vertically aligned multi-walled carbon nanotubes are synthesized by a chemical vapor deposition process with atmospheric pressure (AP-CVD) to two different carrier media, Silicon substrates and Carbon fleece. The CNT-synthesis is attached to two preparation steps, the coating with the diffusion barrier (buffer layer) Al_2O_3 of about 40nm and a precursor layer (catalyst) Iron/Cobalt of about 5nm. Both layers are applied by a multistage immersion process to set the well-defined layer thickness. The AP-CVD process itself is performed in a heating reactor shown in Figure 1. With process temperatures of 650 to 800°C, the substrates are exposed to a mixture of the process gases ethylene (carbon donator), hydrogen and argon, which will enable the CNT growth at the Fe/Co catalyst, while the length of the CNTs correlates with the processing time.

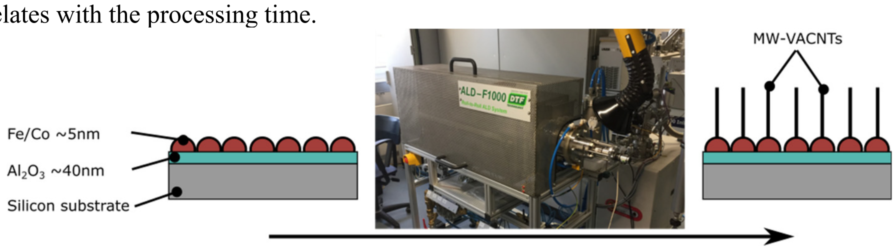

Figure 1. Schematic of the precursor layers on the silicon substrate (left) [8], photograph of the AP-CVD reactor (middle) and schematic of the multi-walled vertically aligned CNTs grown on the iron catalyst (right) [8].

Secondary electron micrographs of the manufactured emitter on its Silicon support and a length of 100µm is shown in Figure 2. The CNTs show slight dispersion in length of about +/-20µm with waves on the surface with a high density. Additionally, the high quality of the MW-CNTs is proven by Raman spectrometric analysis that shows only a fracture of amorphous carbon. Besides this, CNTs are synthesized to an anisotropic carbon based non-woven fabric that is shown in Figure 3. The single carbon fibres of the carbon fleece material as well as the conglomerates of CNT bundles with a high length are visible in the micrograph. Due to the previously described chemical manufacturing process a front- and a backside is discerned.

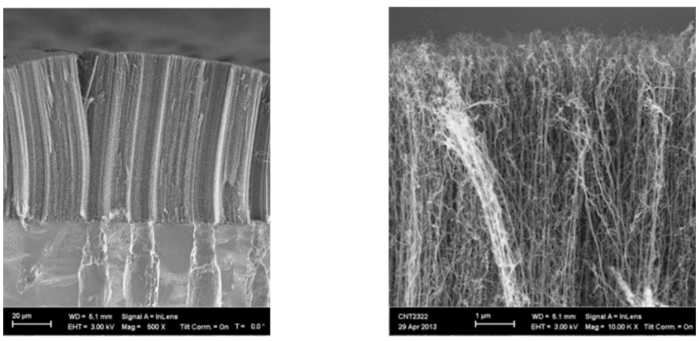

Figure 2. Secondary electron micrograph of vertically aligned multi-walled carbon nanotubes on a silicon substrate. [9]

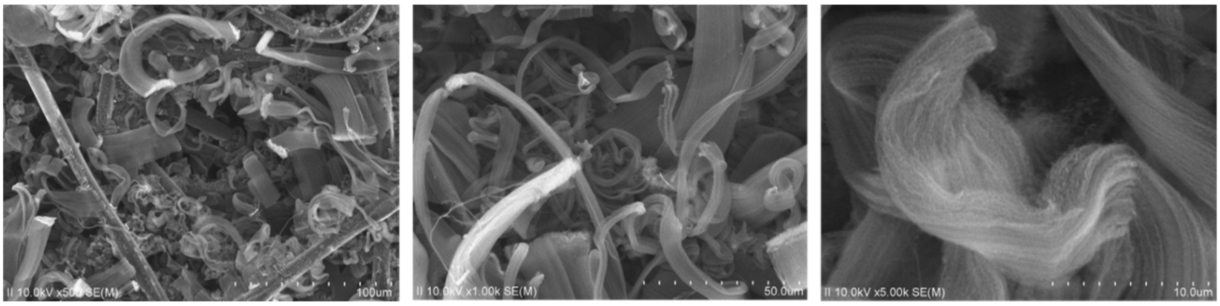

Figure 3. Secondary electron micrographs of the MW-CNTs on carbon fleece.

B. Emission test setup and test configuration

The basic mechanical design of the prototyping setup of the cold electron field emitter is shown in Figure 4 (left) and simplifies the cold electron emitter to its central elements. The lower stainless steel frame keeps the emission material that consists of multitude carbon nanotubes, while PEEK isolators separate the upper frame connected to the gridded counter electrode, called extractor. The prototyping setup allows the emission performance analysis of 6 emitter configurations while retaining a fast and simple variation of the emission materials, the counter electrodes as well as the distances between the elements. The surveyed chip size is 8x8mm².

As shown in Figure 4 (right), only one high voltage power supply is needed to set the emitter to a negative voltage. Both extractor and collector are connected to ground potential via a resistor and fuse protection. The current of electrons reaching the electrodes is measured by the voltage drop at the given resistance. In such a way, detailed analysis of the current loss to the extractor as well as the current emitted to the collector, representing the ambient plasma, can be made.

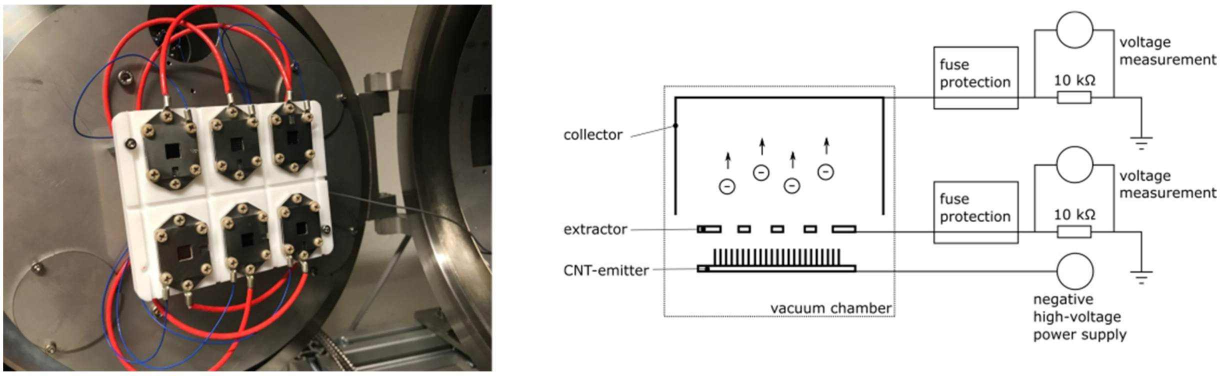

Figure 4. Emission test setup (left) and schematic of the electrical connections for the testing of electron field emitters [3].

Current-voltage characteristics of several electron field emitter configurations and 100h duration tests are performed to initially characterize the general performance data. Significant value is the transmissivity, which is calculated as the ratio of the emitted electrons and the measured electrons at the collector. This value represents the emission efficiency, representing the power loss due to electrons measured at the extractor and not reaching the ambient plasma. A high vacuum condition better than $1.5 \cdot 10^{-6}$ mbar prevents electrical breakdowns and improve the long-term stability of the electron source. Typical experimental data of an early prototyping stage with only 50-60% transmissivity is shown in Figure 5. The current-voltage characteristic shows an ignition voltage of -600V and ramping up to an emission current of 700µA at -1050V. As expected, the duration test shows a fluctuation electrical potential at the CNT-emitter while the emission current is set to a constant value. The electrical potential is intensively rising during the onset of the experiment to a nominal electron emission of 200µA at less than -1000V. Subsequent the voltage is slightly increasing and returning to its initial value. It is assumed that an alternation of the electron emission sites cause the electric potential fluctuation and increase as well as the variation of the current-loss at the extractor.

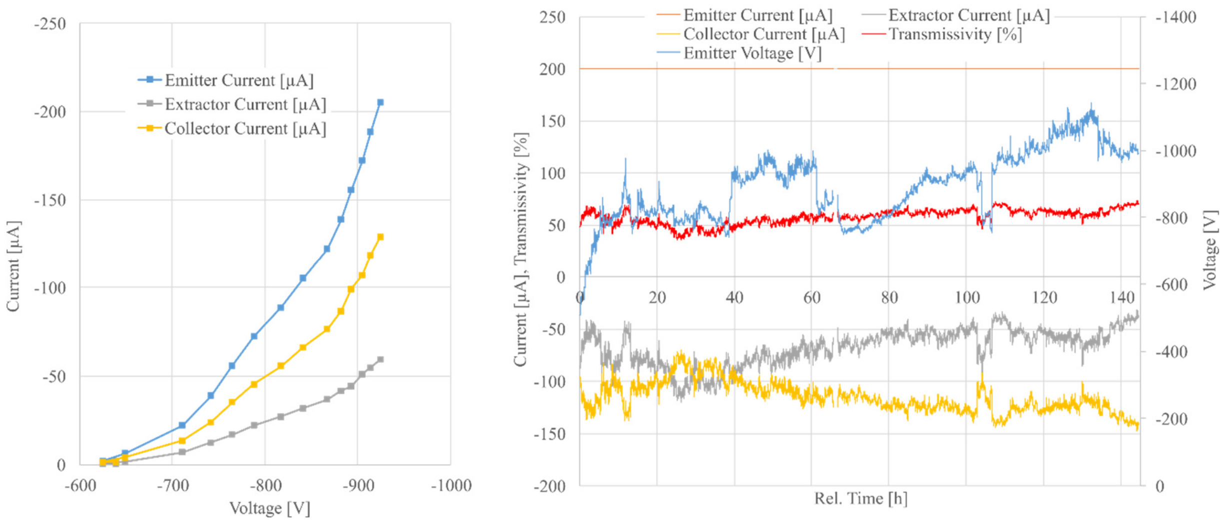

Figure 5. Typical current-voltage characteristics after several operating hours (left) and duration stability of the electron emission (right) of an early CNT-based cold cathode prototype.

Furthermore to the described prototyping setup, an additional gridded electrode biased with the electric potential of the emitter is introduced to the design. With the perfect alignment between the mask and the extractor, the transmissivity is significantly enhanced to values of 75-90%.

C. Cold electron source setup

Photographs of the manufactured and tested cold electron field emitter compared to a 1 Cent coin are shown in Figure 6 in the standard 8x8mm² and in the 16x4mm² configuration, which is in operation on the UWE4-satellite. As the neutralizer design is versatile and scalable, an elongated chip was preferred to place the electron source in the middle of a side panel of the 1U-CubeSat between the solar panels. Additionally, the high-voltage connecting wire is attached in a flat angle to respect the maximum bending radius specification and the constricted space conditions to other subcomponents. Both neutralizers contain electrical insulating PEEK elements, an inner supporting structure to connect the CNT-emitter and the mask as well as an outer supporting structure to insert the extractor electrode. Electrical wires were insulated to the inner PEEK structure to prevent electrical breakdowns to surrounding components. The before-noted dimensions are the maximum surface of the CNT-emitter. Due to mask and extractor coverage, the CNT-area contributing to the electron emission is even smaller. The outer footprint of the standard-configuration neutralizer is 15.5x13.0mm² and 19.5x10.5mm² for the elongated version, while both have an overall height of less than 6mm. The lower ledge enables the definition of the depth and secure positioning when mounted into a test-panel or a CubeSat.

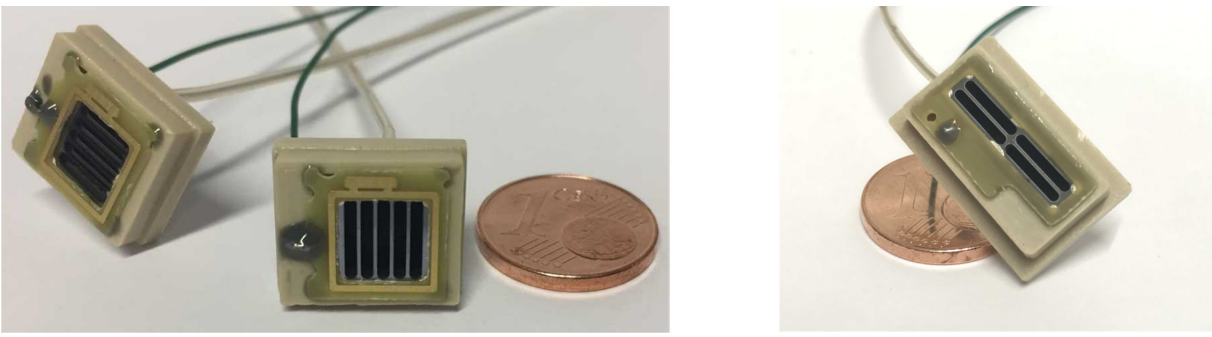

Figure 6. Photograph of the manufactured and tested cold field emitters in the 8x8mm² standard configuration (left) [3] and the 16x4mm² elongated design (right).

D. Laboratory testing

A 100h endurance experiment electron emission current is performed to initially evaluate the performance data (Figure 7). The electron source is mounted to a CubeSat Dummy and again, high vacuum conditions are realized to prevent electrical breakdowns, between the electrodes as well as closed by components. Different from previous experiments the electron current is set to 300µA and again the electrical emission potential is allowed to fluctuate. Initially, the emitter potential is less than -1100V and increases to a maximum value of -2200V after about 65h of continuous operation but returning roughly to its initial value at 85h of operation. The steady voltage increase and sudden rebound are typical for the long-term measurements. Now, with mask-configuration implemented the transmissivity is calculated to be higher than 95% on average. Current-voltage characteristics of the electron source before and after the 100h endurance experiment are shown in Figure 7 (left). Even at this high electron emission currents an average voltage gain of about 200V only is measured.

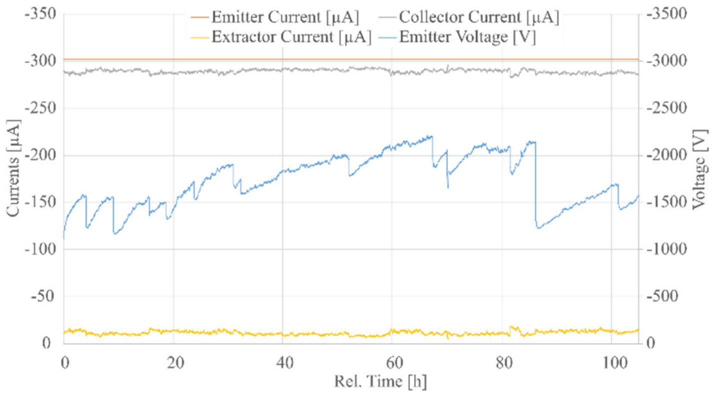

Figure 7. Duration emission stability of the electron source with a high emission current of 300µA [4].

Future space application as electron source for space tethering missions are demanding for higher emission currents as shown before. To determine the limits of the manufactured neutralizer, a duration test about 100h with an emission current of 1mA was performed (Figure 8). The electron emitter potential had a value of less than -1000V at the given electron current with a steady increase of about 5.5V/h. The interruptions visible in the experimental data are intentional to repeatedly examine the current-voltage characteristics as well as necessary reboots of the controlling computer. With about 90h of operation, an event occurred that is leading to a decrease of the transmissivity and a gain of electron loss at the extractor. The path of the leakage current was detected by visual inspection using an optical micrograph at the previously described PEEK supporting elements. Both, the electron emitter and the extractor are inspected by secondary electron micrographs and exhibit a good condition.

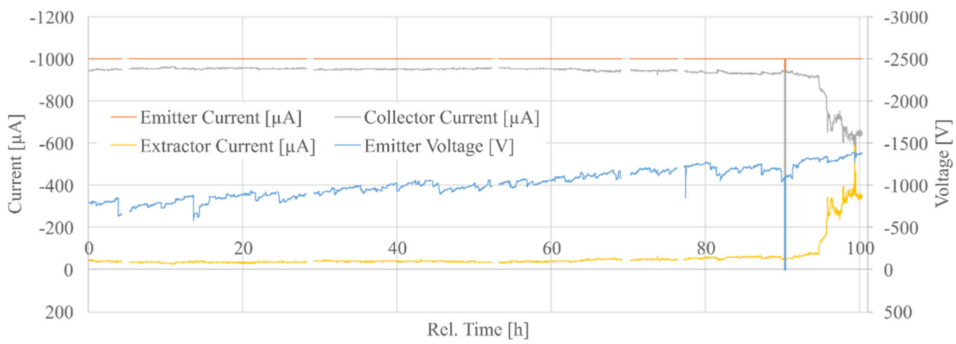

Figure 8. Experimental analysis of the high current limit of 1000µA for continuous operation of the neutralizer.

E. Orbital data

As mentioned before, two of the described neutralizers are in operation next to the four NanoFEEP thrusters on the University Würzburg Experimental Satellite 4, which was launched on the 27th December 2018 into a sun-synchronous low earth orbit with an average altitude of about 600km. One neutralizer has been ignited after the commissioning phase of the satellite but 5 days before the thrusters. As stated earlier, the subsystem is necessary prevent the satellite from negative potential due to the emission of ions from the thrusters. On 26th of February, one thruster has been successfully ignited and the ion current was compensated by the neutralizer, which was the first time an electric propulsion system was activated successfully on a 1U-CubeSat. Both thruster and neutralizer, operated on its nominal voltages as depicted in Figure 9. [2]

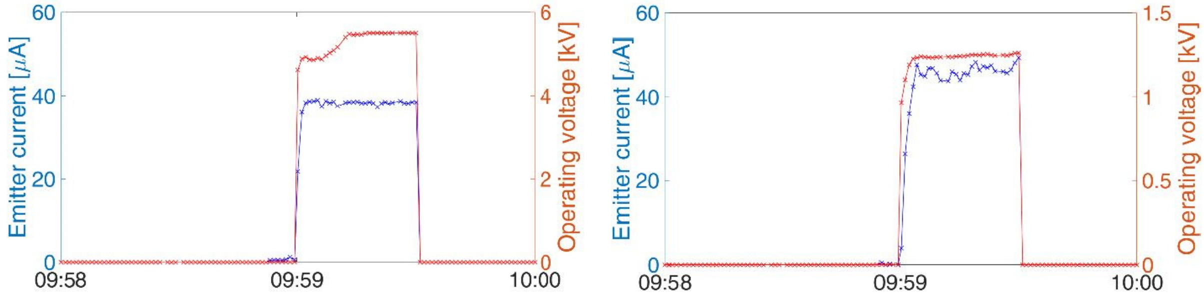

Figure 9. Operation voltage and emitter current of the NanoFEEP thruster (left) and the Neutralizer (right). [2]

III.Conclusion

A CNT-based cold electron field emitter has been developed and tested. After hundreds of hours of continuous operation in laboratory experiments, the prove of concept in space was successfully realized. Therefore, a highly reliable electron source that is operating on low power demand with an extremely small volume and weight without the use of a heater or any propellant/expellant has been realized.

As a next step the long-term electron emission experiments will be continued, while simultaneously increasing the emission currents. A sound strategy would be to cluster the available emitters at a reasonable emission current. Advantages of this are a larger number of equivalent parts with independent control, increasing redundancy, margins and reliability and a minimized potential increase during long-term operation. Having a number of different emitters could also allow for running some of them at their sweet spot voltage, resulting in a significant reduction of power per emission current.

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