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A New Mitigation Method for Space Robot Charging Effect Based on CNTs

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Abstract. Autonomous space robot will be widely used to complete various space missions in future. Unfortunately electrostatic surface discharge (ESD) induced by space plasma environment may produce one of the most common anomaly in space robots. Liquid Metal Ion Source (LMIS) is one of the effective mitigation methods for space robot charging effect. But as a devices for space-robots charging mitigation equipment, has strict requirements to its weight and volume. The present LMIS can only work at a very high voltage, so the weight and volume of LMIS isn't suitable for space robot. Here we propose that carbon nanotubes (CNTs) can be used as capillary-type emitters in LMIS to meet the challenge. Well-aligned CNT arrays are synthesized on self-ordered hexagonal porous anodic aluminum oxide (AAO) template using chemical vapor deposition (CVD) method. The CNTs obtained are monodispersed and have open tip, which indicates that they have the similar geometry to the present capillary-type emitters in LMIS. So the LMIS made of CNTs can emit ions at a very lower voltage. A new mitigation device for space robot charging effects with very small weight and volume can be developed. The key steps for fabricating CNT emitters are presented.

1. Introduction

With the development of space exploration, autonomous space robot will be widely used to complete various missions. Ongoing human missions to space station have an integrated mix of crew working with robots and supporting autonomous systems on-board spacecraft and in mission control. On orbit servicing tasks of spacecraft will be completed mainly by robots in future. Deep-space exploration missions will require many automation technologies to enable safe missions, become more independent, and enable intelligent autonomous operations. Space robots may play a more and more important role in space missions in future. We can expect in the next few decades that robots designed for space missions will approach or even exceed the performance of the astronauts.

However, there are many unresolved challenges in space robots, one of which is natural environment hazard. Various aspects of the space environment can cause on-orbit spacecraft anomalies. Studies have shown that adverse interactions between the natural space environment and space systems can have deleterious consequences comparable to those caused by human or design errors[1]. Electrostatic surface discharge (ESD) is one of the most common anomaly producing mechanisms in spacecraft. Interactions between hazardous space plasmas and spacecraft surfaces often result in spacecraft charging. Such as in geosynchronous orbit, the plasma environment can cause differential charging of satellite components and lead to ESD on spacecraft. Some mitigation methods have been developed for spacecraft, but as a devices for space-robots charging mitigation equipment, has strict requirements to its weight and volume. Lightweight and miniaturization technology must be developed.

2. Liquid Metal Ion Source (LMIS)

The concept of mitigation of spacecraft charging is defined as a method or design which makes spacecraft charging less severe. Emission of electron or ion beams can control the spacecraft potential effectively. One of the spacecraft charging compensator is Liquid Metal Ion Source (LMIS), which can emit ions beams under high voltage [2-4]. Field emission of ions is a key principle used in LMIS, which refers to the process of using a strong electric field to produce a spray of charged ions and droplets from emitters. If the potential difference between an electrode and a liquid metal surface is sufficiently high, the surface is deformed to an equilibrium shaped so called Taylor cone and then ions and droplets are directly pulled out of the liquid metal surface producing thrust [5, 6].

In LMIS, there is a critical minimum electric potential called onset voltage U_0, below which no ions emission will occur, and the liquid metal gradually distorted into a Taylor cone or a series of Taylor cones with the radius of curvature at the apex of these cones becoming smaller and smaller as the voltage increases [7]. It has been presented experimentally that electric filed is extraordinarily high with a value level of 10^9 Vm^{-1} to extract ions [8]. It is very difficult to pull ions out of the liquid metal.

To lower the applied voltage, several type emitters have been used as field-enhanced structure for LMIS due to their small radius of curvature, such as sharpened needles, capillaries or nozzles, slits, rings. But, the radiuses of curvature of the emitters are usually more than 1μm. The application voltage should be above 5, 000V to emit ions in LMIS [9]. So the weight and volume of LMIS is so high that LMIS can’t be used in space robots to mitigate charging effect.

Due to their high aspect ratios and small radii of curvature carbon nanotubes (CNTs) are excellent field emission emitters with high field emission current density at low electric field and stable currents [10-12]. But CNTs used as emitters in LMIS have never been reported. Here a new method to fabricate capillary-emitters used in LMIS is presented. It is shown that the emitters being made of open-end CNTs can emit ions at a much lower voltage about 2, 000V. Such LMIS may be suitable for being used in space robots with much smaller weight and volume.

3. Experimental method

The key processes of fabricating CNT emitters used in LMIS are shown in Figure.1. Firstly, an AAO film was fabricated to be used as template for synthesizing CNTs. When aluminum is anodized as part of an electrolysis cell in the presence of certain weak acid electrolytes, a porous AAO film develops on the surface of the anode. Due to this phenomenon, an AAO template was prepared using a two-step anodization process [13]. A high purity (99.99%) aluminum sheet was ultrasonically washed sequentially with acetone, ethanol, and distilled water. After being annealing in Ar flow at 500℃ for 4h, aluminum sheet was anodized in a 0.3M oxalic acid at 17℃ with a constant supplied voltage of 40V for 3-4 h. Then, the porous alumina film formed was removed by a wet chemical etching in a mixture of phosphoric acid (6 wt%) and chromic acid (1.8 wt%) at 40℃ for 18h. Thereby a relatively ordered indent pattern on the surface of aluminum sheet is prepared. Subsequently, the aluminum sheet was anodized again for 5-6h under the same conditions as in the first anodization process. To separating the AAO film from remaining aluminum film, a wet chemical process is employed to etch the aluminum film by immersing the sample in CuCl2 solution. The barrier layer of AAO film was also removed and the AAO template with high-ordered pores as shown in Figure.1 (A) was obtained.

Secondly, a catalyst-assisted chemical vapor deposition method was used to synthesize well-aligned CNT arrays on self-ordered porous AAO template. The AAO template was immersed in Fe(NO3)3 solution for 10 min, and then washed with distill water. An annealing treatment was carried

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out in air at 300 ℃ overnight to oxidize the iron nitrate To depositing carbon on the surface of the pore in AAO template, the template was placed in a quartz boat sealed at one end, which was then inserted into a quartz tube mounted in a tube furnace. The furnace was heated to 700 ℃ in an argon flow, then a mixture of Ar/H_2 with a volume ratio of 10:1 was flown for 10 min to activate the catalyst. CNTs were synthesized with C_2H_4 as carbon source for 20min, after which the furnace was cooled down to room temperature.

Finally, the tips of CNTs were exposed by a wet etching process in order to form a similar structure of the emitters in LMIS. After CNTs were synthesized by CVD method, the surface of the AAO template is blanketed with clumps of foam-like amorphous carbon as shown in Figure.1 (B). An oxygen plasma treatment was carried out for 10 min to remove the amorphous carbon (Figure.1 (C)).

Then the template containing CNTs was attached on a ring type substrate. At last, the upper side of the AAO template was partially etching away by dissolving it in 5% wt NaOH solution to expose the tips of CNTs (Figure.1 (D)).

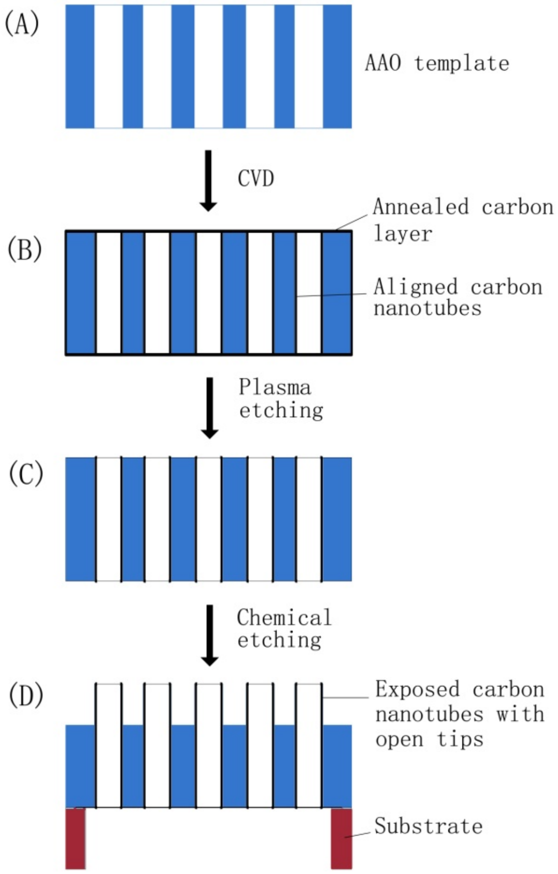

Figure.1 Fabrication steps of CNT emitters

The morphologies of CNTs were characterized by scanning electron microscopy (SEM, JEM-6301F) and transmission electron microscopy (TEM, JEM-200CX).

4. Result and discussion

Figure.2 shows the SEM image of CNTs grown on AAO after chemical etching process. The CNTs are partially exposed with uniform height of about 100nm. The TEM image of CNTs also presents that all CNTs have open tips and large inner diameters (Figure.3). The outer diameters of CNTs are proportional to the pore size in AAO, which indicates that the diameters of CNTs can be controlled by adjusting the pore size in AAO. It had been proved that different pore diameters in AAO could be

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obtained by varying the anodizing voltage because the pore diameter is proportional to the voltage [14]. The height of CNTs exposed can also been controlled by knowing the etching rate of a particular acid and varying the etching time. So optimizing the geometry of the CNT emitters to enable a better performance in LMIS is possible.

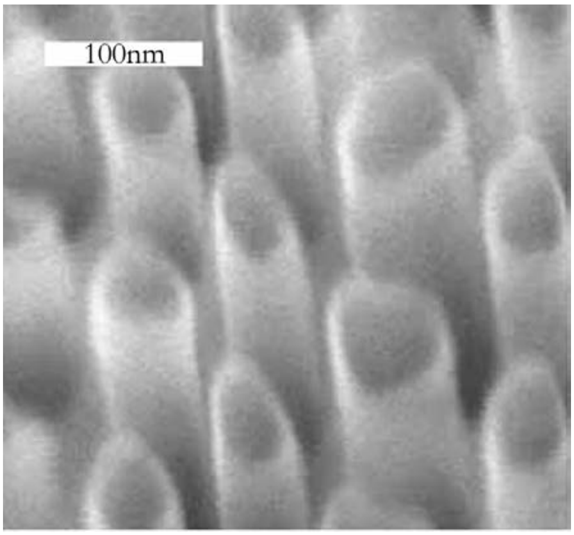

Figure.2 SEM image of CNTs grown on AAO after partially etching away the AAO template

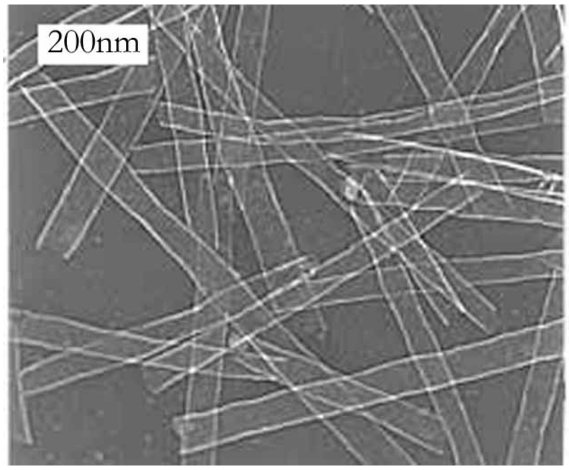

Figure.3 TEM image of CNTs grown on AAO after completely etching away the AAO

The schematics of a LMIS with CNTs as emitters are shown in Figure.4. By capillarity action, liquid metal would fill in CNTs. A voltage is applied between an extractor electrode and CNT emitters, and then a high electric field will extract charged droplets form liquid metal. The droplets are then accelerated by the same voltage and the thrust are produced.

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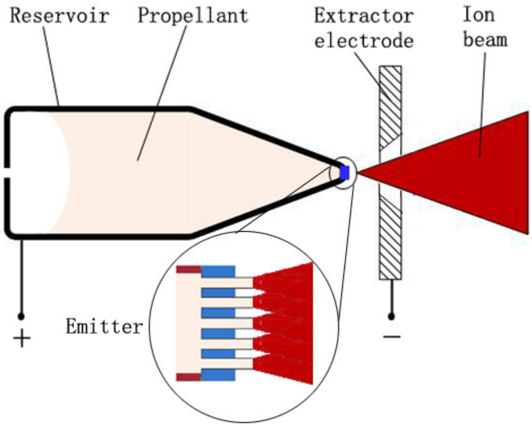

Figure.4 Schematics of a LMIS

To extract charged droplets form liquid metal, a high electric field should be applied on the surface of liquid metal. So a very high voltage usually is used in LMIS. Due to their high aspect ratios and small radii of tip curvature, CNTs are good field emission emitters and have great enhanced field-emission properties. A lower voltage could be enough to extract charged droplets.

Figure.5 shows a simulated result of the electric field intensity between the CNT arrays and the extractor electrode when a voltage of 1000V was applied. The distance between the cathode and the tips of the emitters was about 20 μm. The height of exposed CNTs is 100nm and the distance between two CNTs is 150nm. It is shown that the electric field on the tips of CNTs is about 8.0×10^4kV/m, which is much larger than the average field intensity. The electric field has been enhanced by a factor of 1.6. We also calculated the electric field intensity on the tips of the silicon emitters. Similar structure of silicon emitters had been fabricated by MEMS manufacturing techniques [15]. The diameters of the emitters were miniaturized to 10 μm. The height of the silicon emitters was 10 μm, and other parameters didn't change. The result shows that the electric field on the tips of silicon emitters is about 6.4×10^4kV/m. So CNT emitters have much better enhanced field emission properties than present emitters in LMIS.

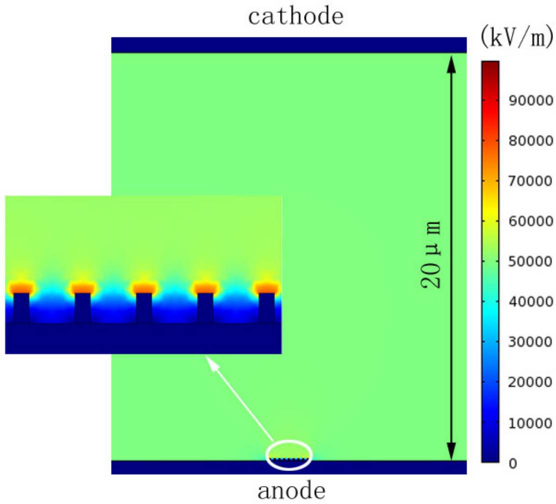

Figure.5 Simulated results of electric field distribution (COMSOL Multiphysics Software)

The ion emission pattern of a prototype sample is shown in Figure.6. When a high voltage of 2000V was applied each time, an emission current occurred simultaneously. The ion beam wasn't very the homogeneous and stable. But it presented that the self-ordered nano-material arrays can be used as emitters in LMIS. With the lower emitting voltage, the weight and volume of LMIS can be reduced.

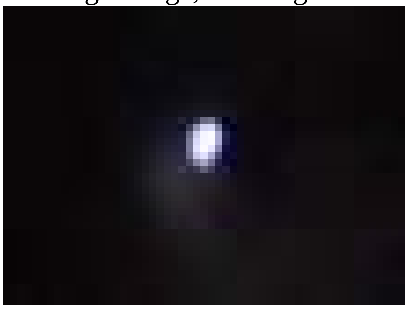

Figure.6 Self-ordered nano-scale emitters during ion emission operation

5. Conclusion

The capillary-type emitters in LMIS should have uniform sizes and distribution. CNTs grown on AAO template are self-ordered and monodispersed with uniform diameter and can be used as capillary-type emitters in LMIS. By this method, small size emitters with diameter of several ten nanometers can be easily realized. With the benefit of the high aspect ratios, the LMIS made of CNTs can emit ions at a very low voltage. So we can develop a new mitigation device for space robot charging effects with very small weight and volume.

References

[1] Garrett H B 1981 *Rev. Geophys. Space Phys.* **19** 577–616
[2] Lai S T 2003 *IEEE Transactions on Plasma Science* **31** 1118-1124
[3] Tajmar M, Scharlemann C, Genovese A, Buldrini N, Steiger W and Vasiljevich I 2009 *Ultramicroscopy* **109** 442–446
[4] Vladimirov V V, Gorshkov V N and Mozyrsky D V 1996 *Appl. Surf. Sci.* 94-94 171-176
[5] Taylor G 1964 *Proc. R. Soc. Lond. A*, **280** 383-397
[6] Marcuccio S and Genovese A 1998 *J. Propul. Power* **14** 774-781
[7] Mair G L R 1980 *Nucl. Instrum. Methods* **172** 567-576
[8] Genoveses A, Tajmar M and Buldrini N 2004 *J. Propul. Powe*r **20** 219-227
[9] Mitterauer J 1987 *IEEE T. Plasma Sci.* **5** 593-598
[10] Rinzler A G, Hafner J H and Nikolaev P 1995 *Science* **269** 1550-1553
[11] De Heer W A, Chatelain A and Ugarte D 1995 *Science* **270** 1179-1180
[12] Bonard J M, Majer F and Stökli T 1998 *Ultramicroscopy* **73** 7-15
[13] Masuda H and Fukuda K 1995 *Science* **268** 1466-1468
[14] Chik H and Xu J M 2004 *Mater. Sci. Eng.* R **43** 103-138
[15] Lenard R, Kravitz S and Tajmar M 2005 *AIP Conf. Proc.* **7** 954-964