Resilient, Nanostructured, High-Current, and Low-Voltage Neutralizers for Electric Propulsion of Small Spacecraft in Low Earth Orbit

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Abstract. We report propellantless neutralizers resilient to oxygen and low-vacuum environments based on arrays of Pt-coated, self-aligned, and gated Si field emitters. These devices emit currents in excess of 1 mA at bias voltages of less than 120 V, adequate for neutralizing the plume of a small spacecraft’s electric propulsion system. The reported devices produce similar currents at fivefold less voltage and emitting area than state-of-the-art CNT neutralizers. Long-term (3 hours) continuous emission in a 1 µTorr oxygen partial pressure environment was demonstrated, confirming the compatibility of these neutralizers with low Earth orbit (LEO) conditions. A robust processing sequence was developed that could be employed for high-yield fabrication of large-area field emission neutralizers with active areas larger than 10 cm² for current emission higher than 100 mA.

1. Introduction

Development of robust, low-power, and high-current neutralizers that do not consume propellant is necessary to advance the state of the art of electric propulsion (EP) systems for small spacecraft. EP systems are particularly attractive for small spacecraft because they deliver thrust at higher specific impulses than chemical rockets, resulting in important propellant mass savings [1]. In EP systems such as field emission electric propulsion thrusters (FEEPs), ion engines, and hall thrusters, a beam of positive ions, i.e., plume, is ejected at high speed to produce thrust [1] - [4]. If the plume is not neutralized, the operation of the electric rocket will negatively charge the spacecraft over time. This built-up charge reduces the propulsion efficiency and eventually stops the thruster. Moreover, it can damage the onboard instruments through arcing and back-ion bombardment. Consequently, neutralizers, i.e. electron sources that maintain the overall charge neutrality of the spacecraft, are an essential part of many EP systems [5].

Currently, neutralizers based on hollow cathodes and hot filaments are employed in state-of-the-art EP systems [6], [7]. Hollow cathodes generate plasma for efficient electron emission at current levels of 100 mA or more with specific currents as high as 10 mA/W [7]. However, these neutralizers are not compatible with miniaturized spacecraft because they consume propellant at rates comparable to the mass flow rate of the plume [8] and they deliver mA-level currents at low specific currents (~0.1 mA/W) [7]. On the other hand, filament cathodes exploit thermionic emission where electrons are excited to vacuum by thermal energy. Hence, these cathodes do not consume propellant but their specific current is typically as low as 1 mA/W [9]. Furthermore, filament cathodes are not suitable for operation at low Earth orbit (LEO) as they quickly degrade when exposed to residual gasses [10].
Field emission neutralizers (FENs) are an attractive option for EP systems of small spacecraft because of their low power consumption, high specific current, small size, and lack of propellant consumption [11]. In field emission (figure 1(a)), electrons tunnel out of the material due to the application of a high electric field that bends the vacuum level and decreases the width of the energy barrier. Consequently, FENs are in principle more energy efficient than thermionic-based neutralizers because of the huge difference in average energy required to emit an electron. The energy required for thermionic emission depends on the thermal capacitance of the cathode which is mostly wasted. The previously reported FENs are based on Spindt-type Mo field emitter arrays (FEAs) [9], [11], carbon nanotube FEAs [12] - [14], Si FEAs with AlN or diamond-like carbon coatings [15], and BN thin-film emitters [16]. For operation in LEO, neutralizers must withstand long-term operation in environments with oxygen partial pressures of ~5×10^{-7} Torr [17]. Carbon nanotube-based FENs could satisfy these requirements; however, they require biases higher than 600 V for 1 mA current emission [14]. Operation at low voltages (<100 V) has been demonstrated using Mo FEAs [9] and AlN-coated FEAs [15]; however, these devices should quickly degrade when exposed to oxygen (~7×10^{-7} Torr), similar to HfC-coated Si [18]. In this work, we report FENs with continuous electron emission of 1 mA with an extraction gate voltage less than 200 V and long-term operation in low vacuum environment with oxygen partial pressures as high as 1×10^{-6} Torr. The FENs are based on nanometer-sharp (< 10 nm radius), Pt-coated, and self-aligned gated Si FEAs (320,000 tips in 0.32 cm²).

2. Pt-coated Si FEN
The schematic of a Pt-coated Si FEN is illustrated in figure 1(b). The device has a self-aligned configuration to maximize the extraction efficiency of electrons. Each FEN has an array of Pt-coated Si tips individually surrounded by a gate electrode with 3 µm-wide aperture. The tips are located 0.7 µm below the gate plane and a 2.5 µm-thick SiOₓ/SiNx stack layer is used as the gate dielectric. The selected device geometry ensures a field factor (β) of ~10⁶ cm⁻¹ for a 5-10 nm radius tip, which results in field emission at voltages as low as 60 V. A thick gate dielectric is necessary for reliable long-term operation so the field in the dielectric is a small fraction of the breakdown field (E_C ~ 800–1000 V/µm) of the dielectric. The tips are coated with Pt to improve their resistance against corrosive gasses and back-streaming ions. A metal mesh, mounted 2 mm above the FEN, is used as a transparent anode to extract electrons while retarding the positive ions approaching the tip array.

Figure 1. (a) Potential energy diagram of electrons at the vicinity of a metal surface w/wo normal electrostatic incident field. (b) Cross-section schematic of field emission neutralizer; the electric field direction is shown with a metal mesh used as anode.

We developed a high-yield process flow to fabricate large-area FEAs that is compatible with array areas larger than 10 cm². First, a thick gate dielectric is incorporated in the device by etching a matrix of Si pillars (3 µm-tall) buried under a 3 µm-thick SiO₂ film. The sample is then planarized until the SiO₂ film is removed from the top of the pillars, and a 200 nm-thick SiO₂ layer is thermally grown over the exposed Si. After this, the gate stack consisting of SiNx (300 nm) and n-Poly Si (200 nm) is deposited and protected by a 200 nm-thick SiO₂ film. Next, the gate aperture and SiO₂ disks over Si
pillars are defined with a concentric mask in a single lithography step to form a self-aligned device structure. Subsequently, the tips are produced over the pillars by isotropic dry etching and oxidation sharpening using the SiO₂ disks as an etch/oxidation mask. Finally, the oxide coating the tips is stripped using HF, and a 10 nm layer of Pt is e-beam deposited over the array. Figure 2(a) shows the optical image of a 0.6 cm × 0.6 cm array with 320,000 tips and a 2 mm × 2 mm gate contact. SEM images of the gated tips with 3 µm aperture are shown in figure 2(b) and 2(c).

3. Neutralizer performance in high vacuum

The field emission characteristics of the device in high vacuum were measured by applying a negative voltage to the emitter while the gate and anode terminals were biased at 0 and 1100 V, respectively. The I-V characteristics of the device as a function of the gate-emitter voltage ($V_{GE}$) are shown in figure 3. At pressures below $5 \times 10^{-8}$ Torr, currents as high as 1 mA are emitted at $V_{GE}$ of less than 120 V with more than 95% transmission through the gate. As expected, the emission current exhibits a linear Fowler-Nordheim behavior at current levels above 50 µA, where the field emission current is larger than the leakage current through the gate insulator (see inset of figure 3). The extracted field factor $\beta$ is $> 10^6$ cm$^{-1}$, in good agreement with electric field simulations.

Figure 4 illustrates the variation in gate and anode currents, as well as the gate-emitter voltage, for a device emitting 1 mA for 20 hrs. The gate current remained below 50 µA during the experiment and variation in $V_{GE}$ was lower than 15 V. The changes in $V_{GE}$ at high vacuum that occur sharply (see data around 11 hours) could be due to mechanical vibrations and poor gate contact. Moreover, the electrical field in the gate insulator of the device is estimated to be less than 50 V/µm, i.e., substantially lower than the critical field of the gate insulator. Consequently, a long-term operation well beyond 20 hours is expected for the device.

Figure 3. Transfer characteristics of FEN; inset shows linear FN behavior with field factor $> 10^6$.

Figure 4. Long-term FEN performance: gate-emitter voltage, anode current, and gate current over time for a device emitting 1 mA.
4. Neutralizer performance in poor vacuum and oxygen residual gas

The performance of the FENs was studied in N₂ and air at pressures of 5×10⁻⁶ and 5×10⁻⁷ Torr. For these experiments, gas was admitted into the chamber through a precision leak valve to set the chamber pressure. The devices were biased at a constant current of 1 mA with anode and gate voltages at 1100 V and 0 V, respectively. After 3 hours of continuous operation, the gas valve was closed to reduce the pressure below 5×10⁻⁸ Torr (the pressure dropped below 5×10⁻⁸ Torr in less than 30 s), and the experiment continued for one more hour. Figure 5 shows the variation of \( V_{GE} \) over time for devices operated at 5×10⁻⁷ and 5×10⁻⁶ Torr in both N₂ and air atmospheres. The FENs had initial gate-emitter voltages of 110-120 V for emission currents of 1 mA at high vacuum (<5×10⁻⁸ Torr). Less than 10 V increase in \( V_{GE} \) was sufficient to maintain 1 mA current for 3 hours in N₂ at 5×10⁻⁷ Torr, and the initial device characteristics were restored by operation of the device in high vacuum. In contrast, degradation in air or at higher pressures in N₂ was faster and not fully reversible. This could be due to passivation of the tip surface by N₂ and O₂ that increases the work function of the emitting surface. This is consistent with the higher impact of O₂ on the device characteristics. Another mechanism for device degradation can be tip damage by ion bombardment, which could be mitigated by reducing the mesh voltage. Interestingly, the gate current of the devices operated in N₂ had higher fluctuations than those exposed to air as illustrated in figure 6. This could be explained by passivation of gate dielectric sidewalls by O₂ that reduces the surface leakage current.

![Figure 5](image_url)

**Figure 5.** Field emission at 5×10⁻⁶ and 5×10⁻⁷ Torr in both N₂ and air atmospheres. Device degradation was reversible after operation in N₂ at 5×10⁻⁷ Torr.

![Figure 6](image_url)

**Figure 6.** Variation of gate current over time during operation of FEN in N₂ and air at 5×10⁻⁶ Torr. The gate current was lower and more stable in air than in pure nitrogen.

5. Conclusions

Arrays of Pt-coated, self-aligned and gated tips are reported as field emission neutralizers for electric propulsion of small spacecraft in low Earth orbit. The neutralizers consist of 320,000 tips with 10 µm pitch and 5-10 nm tip radii, and have an integrated self-aligned gate electrode with 3 µm apertures. The devices emit currents in excess of 1 mA at bias voltages below 120 V, i.e., similar currents at five-fold less bias voltage and emission area than state-of-the-art CNT neutralizers. The devices have a 2.5 µm-thick gate dielectric to prevent device failure due to dielectric breakdown; the tips are coated with a 10 nm-thick Pt film to improve the tip resistance against ion bombardment and reactive gasses. Continuous emission for 3 hours at pressures of 5×10⁻⁶ Torr in air was demonstrated. Less than 60 V increase in the gate-emitter voltage was sufficient to maintain the emission current at 1 mA. As expected, less device degradation was observed at lower pressures and in N₂ compared to air. Nevertheless, degradation rates seem to saturate, suggesting that our FENs could achieve long-term operation at gate-emitter bias voltages below 250 V, which could be easily accommodated as the electric field intensity in the gate dielectric would remain significantly less than the breakdown field of insulator (800–1000 V/µm). Furthermore, FENs with tens of cm² active area and 5-10 µm-thick gate
dielectrics could be fabricated using the same process flow to increase the emission current and device reliability and hence be able to satisfy the requirements of larger electric propulsion systems.

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References
[1] Sutton G. P. 2001 Rocket propulsion elements (New York: John Wiley & Sons)
[2] Tajmar M, Genovese A and Steiger W 2004 Indium field emission electric propulsion microthruster experimental characterization J. Propul. Power 20 211
[3] Brophy J R and Noca M 1998 Electric propulsion for solar system exploration J. Propul. Power 14 700
[4] Cardiff E H, Jamiesont B G, Norgaard P C and Chepko A B 2004 The NASA GSFC MEMS colloidal thruster in Proc. AIAA/ASME/SAE/ASEE Joint Conf. and Exhibit 3592
[5] Tajmar M 2003 Advanced space propulsion systems (Vienna: Springer)
[6] Sengupta A, Brophy J R and Goodfellow K D 2003 Status of the extended life test of the deep space 1 flight spare ion engine after 30,352 hours of operation in Proc. AIAA 4558
[7] Genovese A, Marcuccio S, Petracchi P and Andrenucci M 1996 Neutralization Tests of a mN FEEP Thruster in Proc. AIAA 2725
[8] Hargus W A and Reed G 2002 The air force clustered hall thruster program in Proc. AIAA/ASME/SAE/ASEE Joint Propul. Conf. Exhibit 3678
[9] Marrrese C M and Polk J E 2000 Molybdenum field emission array cathode performance in primarisy xenon environments: Preliminary experimental results at low operating voltages in Proc. AIAA/ASME/SAE/ASEE Joint Propul. Conf. Exhibit 3266
[10] Gross J H 2006 Mass spectrometry: A textbook (Heidelberg, Germany: Springer-Verlag)
[11] Marrrese C M 2000 A review of field emission cathode technologies for electric propulsion systems and instruments in Proc. IEEE Aerospace Conf. 4 85
[12] Aplin K L, Kent B J, Song W and Castelli C 2009 Field emission performance of multiwalled carbon nanotubes for a low-power spacecraft neutraliser Acta Astronautica 64 875
[13] Williams L T, Kumsomboone V S, Ready W J and Walker M L R 2010 Lifetime and failure mechanisms of an arrayed carbon nanotube field emission cathode IEEE Trans Electron Dev. 57 3163
[14] Gasdaska C J, Falkos P, Hruby V, Robin M, Demmons N, McCormick R, Spence D and Young J 2004 Testing of carbon nanotube field emission cathodes in Proc. AIAA/ASME/SAE/ASEE Joint Propul. Conf. Exhibit 3427
[15] Aplin K L, Kent B J, Collingwood C M, Wang L, Stevens R, Huq S E and Malik A 2011 Use of coated silicon field emitters as neutralisers for fundamental physics space missions Adv. Space Res. 48 1265
[16] Goldberg H, Encarnación P, Morris D, Gilchrist B and Clarke R 2004 Cold-cathode electron field emission of boron nitride thin film with a MEMS-based gate for space applications in Proc. AIAA/ASME/SAE/ASEE Joint Propul. Conf. Exhibit 3499
[17] Ceccanti F, Marcuccio S and Andrenucci M 2001 FEEP thruster survivability in the LEO atomic oxygen environment in Proc. International Electric Propulsion Conf. IPEC 295
[18] Nicolaescu D, Nagao M, Sato T, Filip V, Kanemaru S and Itoh J 2005 Emission statistics for Si and HfC emitter arrays after residual gas exposure J. Vac. Sci. Technol. B 23 707