

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 μ Torr 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 (FEEP), 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 $\sim 5 \times 10^{-7}$ 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 ($\sim 7 \times 10^{-7}$ 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 cm^2).

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 $3 \mu\text{m}$ -wide aperture. The tips are located $0.7 \mu\text{m}$ below the gate plane and a $2.5 \mu\text{m}$ -thick $\text{SiO}_x/\text{SiN}_x$ stack layer is used as the gate dielectric. The selected device geometry ensures a field factor (β) of $\sim 10^6 \text{ cm}^{-1}$ 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 ($E_c \sim 800\text{--}1000 \text{ V}/\mu\text{m}$) 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.

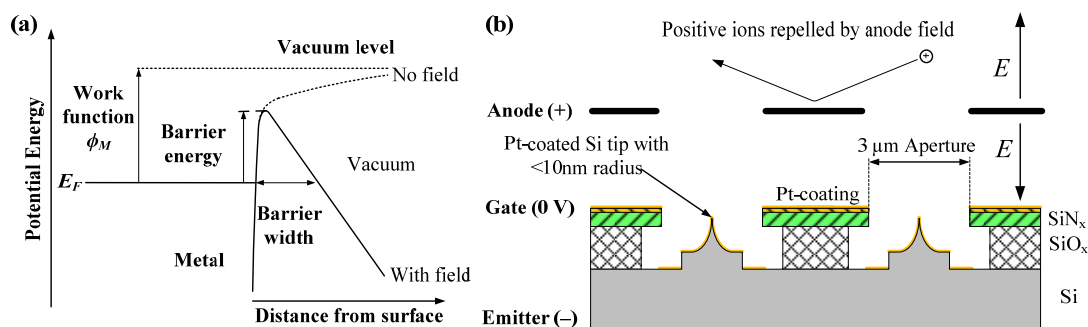


Figure 1. (a) Potential energy diagram of electrons at the vicinity of a metal surface w/o normal electrostatic incident field. (b) Cross-section schematic of field emission neutralizer; the electric field direction is shown with a metal mesh used as anode.

We developed a high-yield process flow to fabricate large-area FEAs that is compatible with array areas larger than 10 cm^2 . First, a thick gate dielectric is incorporated in the device by etching a matrix of Si pillars ($3 \mu\text{m}$ -tall) buried under a $3 \mu\text{m}$ -thick SiO_x film. The sample is then planarized until the SiO_x film is removed from the top of the pillars, and a 200 nm -thick SiO_2 layer is thermally grown over the exposed Si. After this, the gate stack consisting of SiN_x (300 nm) and n-Poly Si (200 nm) is deposited and protected by a 200 nm -thick SiO_x film. Next, the gate aperture and SiO_2 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 SiO_2 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 $0.6 \text{ cm} \times 0.6 \text{ cm}$ array with 320,000 tips and a $2 \text{ mm} \times 2 \text{ mm}$ gate contact. SEM images of the gated tips with $3 \mu\text{m}$ aperture are shown in figure 2(b) and 2(c).

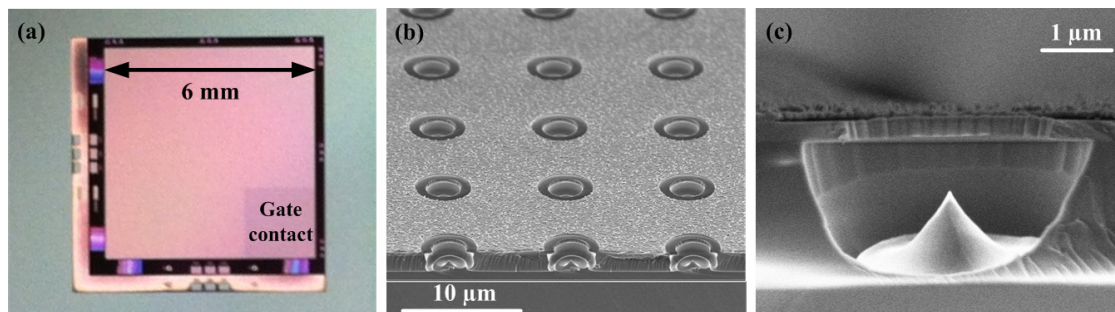


Figure 2. (a) Optical image of a field emitter neutralizer; (b) angle-view and (c) cross-section SEM images of self-aligned gated tips.

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 5×10^{-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 $50 \mu\text{A}$, where the field emission current is larger than the leakage current through the gate insulator (see inset of figure 3). The extracted field factor β is $> 10^6 \text{ cm}^{-1}$, 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 $50 \mu\text{A}$ 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 $50 \text{ V}/\mu\text{m}$, 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.

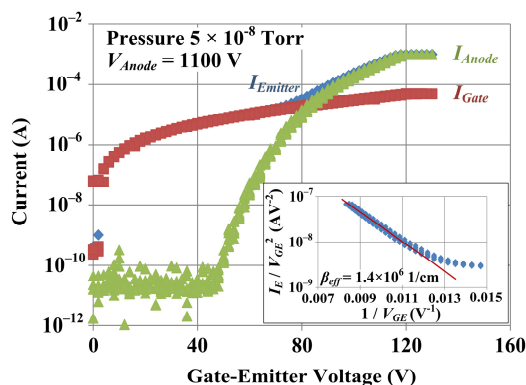


Figure 3. Transfer characteristics of FEN; inset shows linear FN behavior with field factor $> 10^6$.

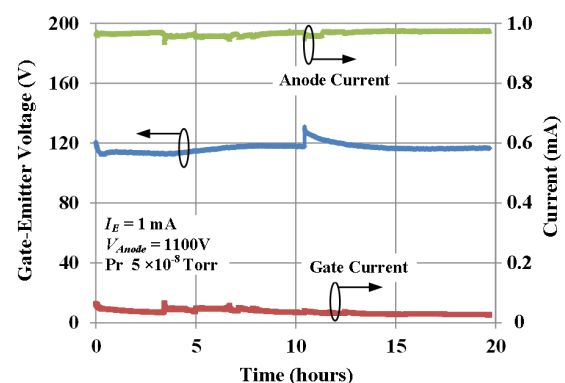


Figure 4. Long-term FEN performance: gate-emitter voltage, anode current, and gate current over time for a device emitting 1 mA.

4. Neutralizer performance in poor vacuum and oxygen residual gas

The performance of the FENs was studied in N_2 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 N_2 and air atmospheres. The FENs had initial gate-emitter voltages of 110–120 V for emission currents of 1 mA at high vacuum ($< 5 \times 10^{-8}$ Torr). Less than 10 V increase in V_{GE} was sufficient to maintain 1 mA current for 3 hours in N_2 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 N_2 was faster and not fully reversible. This could be due to passivation of the tip surface by N_2 and O_2 that increases the work function of the emitting surface. This is consistent with the higher impact of O_2 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 N_2 had higher fluctuations than those exposed to air as illustrated in figure 6. This could be explained by passivation of gate dielectric sidewalls by O_2 that reduces the surface leakage current.

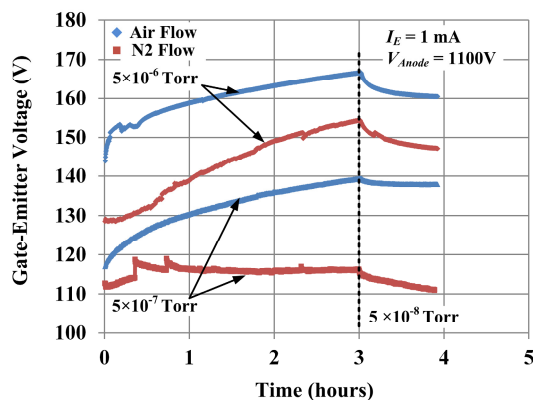


Figure 5. Field emission at 5×10^{-6} and 5×10^{-7} Torr in both N_2 and air atmospheres. Device degradation was reversible after operation in N_2 at 5×10^{-7} Torr.

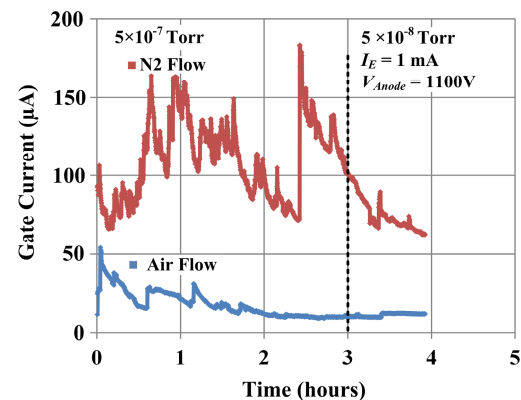


Figure 6. Variation of gate current over time during operation of FEN in N_2 and air at 5×10^{-6} Torr. The gate current was lower and more stable in air than in pure nitrogen.

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 N_2 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 cm^2 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.

Acknowledgment

The devices were made at the Microsystems Technology Laboratories of the Massachusetts Institute of Technology. This work was funded in part by the Defense Advanced Research Projects Agency / Microsystems Technology Office, contract W31P4Q-10-1-0005 (Program Manager A. Shkel). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the US Government and therefore, no official endorsement of the US Government should be inferred.

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