Regenerable Field Emission Cathode for Spacecraft Neutralization

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This research investigates the discharge characteristics of a field emission cathode for use in electric propulsion that has the ability to be regenerated when the emitter tip becomes damaged. Emitter tip regeneration is achieved by taking advantage of Taylor cone formation from an operating liquid–metal ion source. Tip formation is accomplished by solidifying, or quenching, the ion-emitting cone to preserve the sharp protrusion so that it can then be used for electron emission. Electron emission I-V curves were taken after tips were formed by quenching the liquid–metal ion source at ion discharge currents ranging from 1 to 25 μA. Fowler–Nordheim modeling was then used to estimate the emitter tip radii of each quenched liquid–metal ion source. Results of the Fowler–Nordheim modeling were promising, showing the ability to regenerate tips and to control the features of the resulting tips by varying the ion current during the quench process. The set of experiments that are reported demonstrated the regeneration process of emitter tip radii ranging from approximately 30–45 nm from a tip quenched at 2 μA down to tip radii of 15–22 nm when quenched at 25 μA.

Nomenclature

\[ A = \text{total emitting area, } \text{m}^2 \]
\[ \alpha = \text{Fowler–Nordheim term [see Eq. (2)]} \]
\[ \alpha' = \text{Fowler–Nordheim term [see Eq. (3)]} \]
\[ E_t = \text{local electric field, V/m} \]
\[ I = \text{discharge current, } \text{A} \]
\[ k = \text{empirical relation for tip radius and gap spacing} \]
\[ r_e = \text{emitter tip radius, } \text{m} \]
\[ V_{\text{max}} = \text{extraction voltage required for } 0.5 \mu\text{A of emission current, V} \]
\[ V_{\nu} = \text{extraction voltage, V} \]
\[ \alpha = \text{Nordheim image-correction term} \]
\[ \mu = \text{Fowler–Nordheim term} \]
\[ \phi = \text{work function, eV} \]

I. Introduction

INTEREST in the miniaturization of space propulsion has been growing over the past 10 to 15 years. The Darwin infrared space interferometer and the Laser Interferometer Space Antenna (LISA) [1] are examples of missions that require technology capable of producing 0.1 to 1000 μN of thrust with low thrust noise and high thrust precision. Two ideal candidates that could meet the thrust requirements are the colloid micronewton thruster (CMNT) and the field emission micropropulsion (FEEP) thruster [1–3]. CMNT and FEEP thrusters are unique in that they do not require a cathode for propellant ionization. However, a neutralizer is still necessary to maintain spacecraft neutrality, because an operating FEEP thruster will still cause a global charge imbalance on a spacecraft. Because CMNT and FEEP thrusters operate using only a few watts of power and very little propellant, traditional neutralizers cannot be used, due to their relatively massive propellant and power requirements. Most traditional neutralizers require an inert-gas flow and heater power to thermionically emit electrons [4]. From a propellant consumption and power requirement standpoint, the thruster efficiency for a CMNT or FEEP thruster would be extremely low if a cathode were used that required more propellant and power than the thruster itself. Therefore, a low-power neutralizer with minimal propellant requirements would be ideal.

One solution is the field emission cathode. Field emission cathodes use nanoscale sharpened electrodes with locally enhanced electric fields to stimulate electrons to escape from the surface of the electrode into vacuum via a quantum tunneling effect known as Fowler–Nordheim emission. If the electric field at the sharp electrode is great enough (greater than 10⁶ V/m), electrons can essentially leak through the potential barrier at the metal surface by applying a potential between the sharp electrode and an extraction electrode, as shown in Fig. 1 [5]. Because the local electric field is inversely proportional to the electrode tip radius, the sharper the emitter tip, the lower the electric potential needed to obtain electron field emission [6]. A tungsten single-needle field emitter typically has a tip radius on the order of tens of nanometers to a few microns and can produce up to 100 μA of electron emission current [5].

Field emission cathodes are used as neutralizers for space propulsion devices and as electron sources for flat-panel displays, focused electron beams for electron microscopy, and neutralization for spacecraft mass spectrometry [6–9]. The motivation for the research reported here is the limited lifetime of many current microfabricated field emitters, with the exception of carbon nanotube cathodes, which have demonstrated impressive life tests [10]. With most field emission cathodes, as electron discharge is continued for long periods of time, the emitter tip begins to wear and blunt. In 2007, Makela and King [11] proposed and demonstrated a technique for regenerating emitter tips using a liquid–metal ion source (LMIS) to construct nanoscale metal structures intended for use as electron field emission neutralizers for space applications. Historically, LMISs have found extensive use as ion sources of high brightness in focused-ion-beam materials-processing applications [12] and, more recently, as electric propulsion (EP) thrusters via the FEEP technology mentioned previously [13–15]. In an LMIS or FEEP thruster, an intense electric field is created near the surface of a low-melting-temperature liquid metal, such as indium, by a downstream electrode. A balance between the liquid surface tension and the electrostatic force between the liquefied metal and the downstream electrode causes a structure known as a Taylor cone to form in the liquid, as shown in a micrograph taken from Driesel et al.’s work [16] in Fig. 2. Because the Taylor cone has a very sharp tip, geometric