Operation of a segmented Hall thruster with low-sputtering carbon-velvet electrodes

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Carbon fiber velvet material provides exceptional sputtering resistance properties exceeding those for graphite and carbon composite materials. A 2 kW Hall thruster with segmented electrodes made of this material was operated in the discharge voltage range of 200–700 V. The arcing between the floating velvet electrodes and the plasma was visually observed, especially, during the initial conditioning time, which lasted for about 1 h. The comparison of voltage versus current and plume characteristics of the Hall thruster with and without segmented electrodes indicates that the magnetic insulation of the segmented thruster improves with the discharge voltage at a fixed magnetic field. The observations reported here also extend the regimes wherein the segmented Hall thruster can have a narrower plume than that of the conventional nonsegmented thruster. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2168023]

In the segmented Hall thruster,[1,2] ion-induced sputtering of the segmented electrodes may produce contamination leading to a conductive coating on the ceramic part of the thruster channel.[2] Such a coating can cause an increase of the discharge current and instability of the thruster discharge leading to the thruster performance degradation. In this work we investigate the operation of a Hall thruster with segmented electrodes made from carbon fiber velvet bonded on carbon substrates.[3] Sputter-resistant properties of this material are exceptional, particularly, with respect to the backflow of contamination.[3,4] This is because ions strike the velvet at grazing incidence and sputtered particles get trapped in the velvet texture.[3] The total sputtering yield of carbon fiber velvet was shown to be several times lower than for carbon-carbon composite materials and graphite.[4] However, the low density of the velvet material may cause faster wear than that of a denser carbon-carbon composite surface or a high-density graphite surface.[4]

An important feature of carbon velvet is that because of interfiber cavities with a large aspect ratio of $\sim 10^2$ it is expected to suppress both ion-induced and electron-induced secondary electron emissions (SEEs) from the electrode. Without SEE, the electron energy losses at the channel walls are lower and the contribution of electron-wall collisions to the electron cross-field mobility (so-called near-wall conductivity) in the thruster discharge is negligible.[5,6] At the same time, the electric-field enhancement at a fiber tip may induce electron field emission, which can, in principle, affect the plasma-wall interaction in a similar manner as SEE.

Previous studies reported the use of a similar carbon fiber velvet material for short-pulse cathodes of high-power microwave tubes,[7] for the SEE reduction from plasma plume probes,[8] and for the protection of vacuum chamber walls against sputtering[3] in plasma thruster facilities. Here, we discuss durability of the velvet electrodes in the continuous plasma discharge of a Hall thruster.

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A 2 kW Hall thruster (Fig. 1) was operated in a 28 m^3 vacuum vessel equipped with cryogenic pumps. The thruster, facility, and diagnostics used in these experiments are described elsewhere.[9] The thruster channel is made of grade HP boron nitride ceramics. For the segmented thruster configuration, two velvet electrodes with lengths of 4 and 6 mm (Figs. 1 and 2) were placed on the inner and outer channel walls, respectively. Carbon fibers have diameter of $\sim 5 \times 10^{-3}$ mm and length of $\sim 0.5-2$ mm. The separation distance between fibers is roughly 0.02 mm. For the nonsegmented thruster configuration, the velvet electrodes were substituted with the boron nitride spacers. In each configuration, the thruster was operated at constant xenon mass flow rate of about 2 mg/s. The background pressure did not exceed 6 μtorr. A commercial hollow cathode neutralizer was operated in a self-heating mode due to the main thruster discharge. The magnetic field (Fig. 1) was held constant.

The measured quantities are limited to the discharge current and voltage, ion flux from the thruster, and floating po-

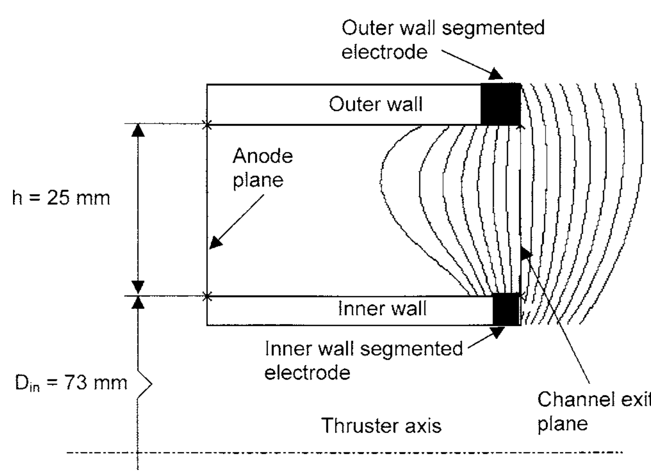

FIG. 1. Schematic of the thruster channel of a 2 kW segmented Hall thruster with superimposed magnetic field lines. The magnetic field distribution was simulated for the experimental conditions. A 4-mm-long inner and 6-mm-long outer segmented electrodes are made of carbon velvet material.

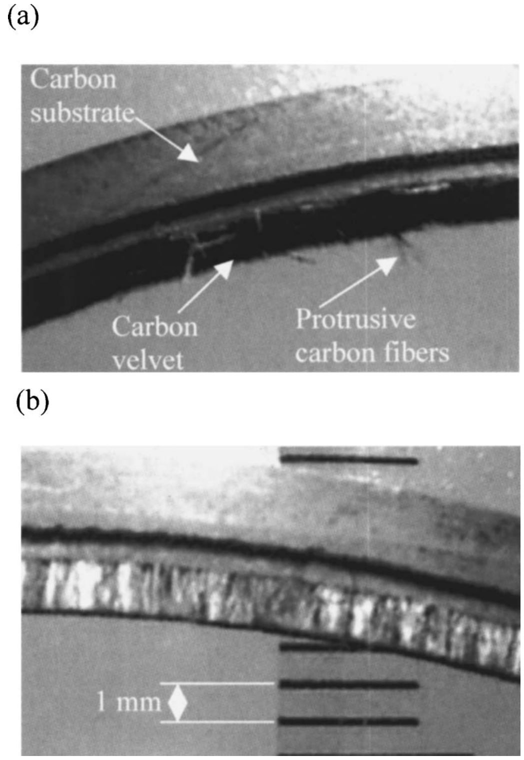

FIG. 2. The outer segmented electrode made of the material—carbon fiber velvet bonded on a carbon substrate—before (a) and after (b) thruster operation.

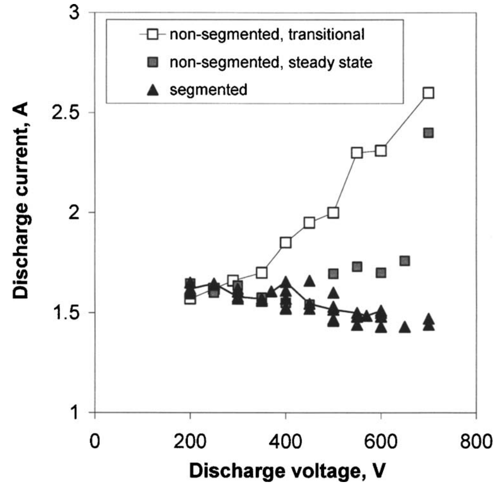

FIG. 3. The voltage vs current (V-I) characteristics for the segmented and nonsegmented thruster configurations. For the nonsegmented thruster, the V-I characteristics were measured in the transitional and steady-state regimes. The magnetic field is held constant.

tentials of the electrodes with respect to ground. The total ion flux from the thruster is obtained by integrating over the measured ion flux angular distribution. The ion flux is measured with a guarding sleeve electrostatic probe[9] rotated around the center of the thruster exit plane at the distance of 730 mm. From the total ion flux and discharge current measurements we deduced the current utilization, I_i/I_d, which characterizes how effectively the magnetic field impedes the electron cross-field current. The plume angle was estimated for 90% of the total ion flux. The standard deviation of the plume angle measurements is less than ±2.5%.

For the segmented thruster, the measurements were carried out with floating electrodes. During the first hour of the segmented thruster operation (total operating time was ~50 h) we encountered arcing between the velvet electrodes and the plasma. We now consider a possible mechanism of this arcing. Because of large axial gradients in the thruster plasma, the sheath voltage drop V_0 between the plasma and equipotential electrode surface increases towards the anode.[5,6] For high discharge voltage regimes (>400 V), floating potentials of the segmented electrodes relative to the cathode are approximately equal to zero. Therefore, we can expect that the sheath voltage drop on the anode side of each electrode is comparable with the discharge voltage.[6] Assuming a steady-state sheath, we can exploit Child's law[10] to obtain the sheath thickness s and the electric field $E = 4/3(V_0/s)$ at the segmented electrode. For a typical Hall thruster operated at the discharge voltage of 200–700 V, the plasma density is 10^{11}–10^{12} cm^{-3} and the electron temperature is 20–60 eV.[9] Under such conditions, the sheath thickness for the segmented electrode is expected to be 0.1–1 mm. For a protrusion with a radius r and a length l, the electric-field enhancement,[11] $\beta \approx l/r$, reaches its maximum in the sheath when $l \approx s$. Then, the maximum possible electric field at the protrusion, $E_m \approx \beta E$, scales as $E_m \propto V_0/r$. According to the Fowler-Nordheim law,[12] the field strength of $E > 10^3$ kV/mm is required to produce an appreciable field-emission current. Thus, for field emission at $V_0 \sim 200$–700 V, microprotrusions have to be less than 10^{-3} mm in diameter, which is not unreasonable for the fiber velvet material used for the segmented electrodes (e.g., the fibers may have sharp tips, possibly thinned fibers etc).

Because of the axial sheath variation, the uniformity of the floating potential of the segmented electrode is maintained by the short-circuit current through the electrode wall.[2,5] The electron emission from the electrode can significantly change the global current balance, which governs the floating condition of the electrode. The current through high resistance fibers is accompanied by the Joule heating.[13] In addition to ion-induced sputtering of the protrusive fibers, excessive heating of these fibers may eventually lead to their destruction.[7,13] This may explain a substantial reduction of the arcing after the initial conditioning time (~1 h) of the thruster operation. Among possible current-driven destruction mechanisms are evaporation of microprotrusions and protrusive fibers, and fiber removal due to a stronger Joule heating at higher electrical resistance points along the fiber (e.g., fiber-substrate contact points, etc).

The operation of the nonsegmented thruster at high discharge voltages exhibits a long (up to 1 h) transitional regime, which precedes the steady-state operation.[9,14] During the transitional operation, the discharge current is always larger than the steady-state value (Fig. 3). It is actually not clear whether the transitional regime is associated with the thruster reaching a thermal steady state[14] or one of these operating regimes is caused by sputtering and coating effects in the laboratory environment.[15,16]

A strong SEE from ceramic channel walls was suggested as an explanation of the V-I characteristics at high discharge

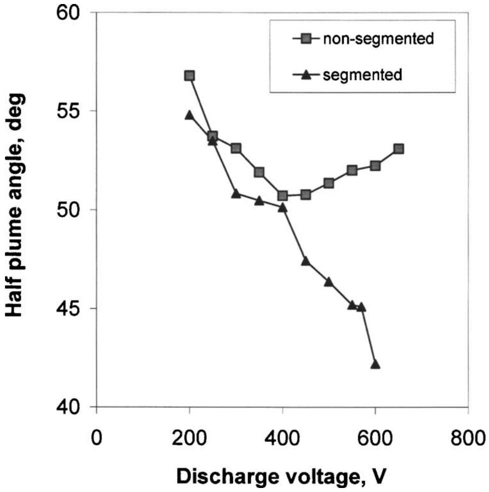

FIG. 4. The comparison of half-plume angle (estimated for 90% of the total ion flux) measured for the nonsegmented thruster in a steady-state regime and for the segmented thruster with velvet electrodes. The magnetic field is held constant.

voltages.[5] For the transitional regime, it is indeed the increase of the electron current that leads to the increase of the discharge current and, thereby, causes the degradation of the current utilization from ~70% at 300 V to ~50–60% at 600 V.[17] Surprisingly, in the steady-state operation, the reduction of the current utilization is not so significant: from ~75% at 300 V to about 70% at 600 V.

Interestingly, for the segmented thruster, there is no transitional regime. The discharge current does not grow with the discharge voltage, while the ion flux is roughly constant, ~85% of the neutral gas flow. Above 400 V, the current utilization increases to about 80%.[17] Finally, Fig. 4 demonstrates that the segmented thruster with the carbon velvet electrodes produces a narrower plasma plume than the conventional thruster.

In conclusion, we demonstrated the use of low-sputtering and low-SEE carbon velvet materials in the continuous plasma discharge of a Hall thruster. A certain conditioning time is required in order to avoid the arcing between the velvet electrodes and the plasma. Note that a typical operating procedure of conventional Hall thrusters requires an increase of the magnetic field with the discharge voltage in order to suppress the increase of the electron current.[14] Apparently, for the segmented thruster this is no longer a requirement. The plume narrowing effect of the carbon velvet electrodes is qualitatively consistent with the previously reported results[2] for a different Hall thruster with segmented electrodes made from carbon or molybdenum.

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