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JOURNAL OF APPLIED PHYSICS **110**, 093301 (2011)

Electron-emission yield under electron impact of ceramics used as channel materials in Hall-effect thrusters

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We report measurement of electron-emission yield (EEY) under the impact of electrons on materials of Hall-effect-thruster (HET) interest: BN, BN–SiO_2, and Al_2O_3. The effects of the material aging (under electron irradiation) on the yield of BN and Al_2O_3 are investigated. The EEY of BN grows with electron exposure, whereas that of Al_2O_3 reduces. A simple analysis of our experimental results indicates that these variations are most likely because of surface and near surface composition changes caused by the electron beam. The representativeness of EEY measurements on ceramics that have not suffered from the specific environment of a HET (ion and electron bombardment) is discussed. © *2011 American Institute of Physics*. [doi:10.1063/1.3653820]

I. INTRODUCTION

Hall-effect thrusters (HET) allow thrust generation by acceleration of neutralized plasma in an electrostatic field. The plasma is obtained by electron bombardment of the propellant gas (typically xenon) inside the thrusters' discharge channel. The specificity of this technology is that electron streaming to the positively biased anode is limited by the presence of a magnetic field normal to the accelerating electric field. This plasma has to be physically contained and this role is played by HET channel ceramics. It was experimentally established that the ceramic nature is not neutral for thrusters operations.[1–5] A number of physical models link the limitation of the energetic efficiency of the HET to the electron-emission yield (EEY) of channel material.[6–9] The EEY is defined as the ratio of emitted electron number (backscattered and secondary electrons) to the incident electron number. According to these models, the lower the EEY of the channel material, the higher the maximum attainable electron temperature. To improve Hall-effect-thruster capabilities for deep-space missions, efforts are being made to push the limits of each component of the materials utilized. In particular, the use of HET materials with low EEY appears as essential. The knowledge of the electron-emission yield is therefore highly required. In particular, the first crossover energy (incident electron energy for which the EEY is one) must be known. However, measurement of EEY is quite difficult because the charge trapping in the ceramics affects the emission yield itself.[10–12] In addition to charging effects, the measurement is made more difficult because the EEY is required for very low incident electron energies (few eV to tens of eV). At low energies, the electron trajectories are highly sensitive to sightless electric or magnetic disturbance. The effects of these disturbances on the measurement of the EEY are discussed in Ref. 10. Data on the electron emission of insulator materials at low energies are very scarce: to our knowledge, only Viel-Inguimbert[14] and Dunaevsky *et al*.[15] have measured the EEY for materials of HET interest. In this paper, EEY measurements on several materials (Al_2O_3, BN, and BN–SiO_2) used as ceramic channel materials are presented. The interest is more focused on exploring the effects of aging under electron irradiation on the EEY than on the yield measurement itself. The representativeness of EEY measured on materials that have not suffered from the specific environment of a HET (ion and electron bombardment) is discussed in the light of the experimental results.

II. EXPERIMENTAL SETUP

Three ceramics were analyzed: BN (h–BN, hot-pressed sintering), BN–SiO_2 (Saint-Gobain, M26 grade: 60% h–BN, 40% fused silica), and Al_2O_3 (purity $> 99.7\%$). The samples are discs of 20-mm diameter and 2-mm thickness. The experimental facility used for EEY measurement is described in Ref. 16. The vacuum level is maintained below 5×10^{-7} mbar, thanks to a cryogenic pump associated with oil-free molecular-diaphragm pumps. The sample is mounted in a holder that can be positioned so that the electron beam strikes the entire sample surface. The electron beam incidence is set normal to the sample surface. The incident charge is measured using a Faraday cup connected to a 350-MHz TDS5034B oscilloscope through a Femto-DHPCA-100 high-speed and a low-noise current amplifier. An ELG2 Kimball instrument electron gun (3 eV–2000 eV) with a μs electron beam pulsing capacity was used as the electron source. The sample surface could be measured with a high-sensitivity (3-mV) Trek-6000B-15 C Kelvin probe, connected to Trek-323 electrostatic voltmeter. All the measurements are performed at room temperature.

The Kelvin-probe (KP) method[13,16] is a three-step method (see Fig. 1). In the first step (i), the surface potential of the sample is measured with the KP and adjusted to an initial negative surface potential value V_{Si}. V_{Si} is adjusted so that the surface potential is always kept negative during the electron pulse with respect with the grounded inner shell of the vacuum chamber. This ensures that all electrons reaching the sample surface from within the sample are truly emitted. In the second step (ii), the KP is removed and the sample is irradiated by a pulse of charge Q_i. In the third step (iii), the KP is repositioned in front of the sample surface to measure the new value of the surface potential, V_{Sf}. The surface

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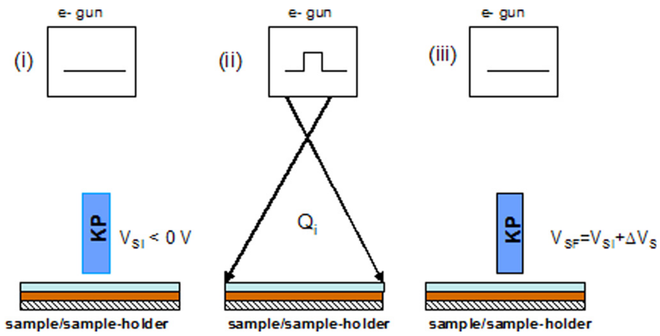

FIG. 1. (Color online) The three steps of the electron-emission-yield measurement with the KP method.

potential variation $\Delta V_S = V_{Sf} - V_{Si}$ can be either positive or negative depending on whether the EEY is greater or less than one. Pulse fluence is adjusted to limit ΔV_S within the range -2 V to $+2$ V. This surface potential variation modifies electron impinging energy. The difference between the average impinging energy during a pulse and the initial impinging energy is below 1 eV.

A 50-μm sample of kapton is introduced between the rear sample surface and the sample holder to prevent leakage current between the sample and the sample holder. The sample/kapton/sample-holder system forms a capacitance C. Knowing C, the electron-emission yield is given by Eq. (1),

$$\sigma = 1 - \frac{C\Delta V_S}{Qi}. \tag{1}$$

Between two electron pulses the sample is discharged. This is achieved by alternating short electron pulses where $\sigma < 1$ when the sample is positively charged and where $\sigma > 1$ when the sample is negatively charged.[17–19] Note that the "as received" ceramics are usually charged before being exposed to electron beams and may in some cases exhibit a surface potential of tens to hundreds of volts (positive or negative). For instance, a positive surface potential of 67 V was measured on the BN–SiO_2 sample, whereas a negative surface potential of -49 V was measured on Al_2O_3. Therefore, the discharging procedure must be systematically applied prior to the measurement of the yield. Note that this discharging procedure only screens the electric field produced by this initial charge but does not remove this charge if it is trapped deep into the sample volume. The capacitance C was measured in situ thanks to the method described in Ref. 12. For this purpose, V_S was set to $+50$ V by biasing the sample holder. The sample surface is then irradiated with pulses of 5 eV. Because of the high positive V_S and low energy incident electrons, we may reasonably assume that the emission yield is almost zero and that the entire incident charge remains on the sample surface. C is then deduced from the slope of the Q_i-versus-ΔV_S characteristic shown in Fig. 2. For instance, C is found to be 3.2 pF for the BN/sample-holder system.

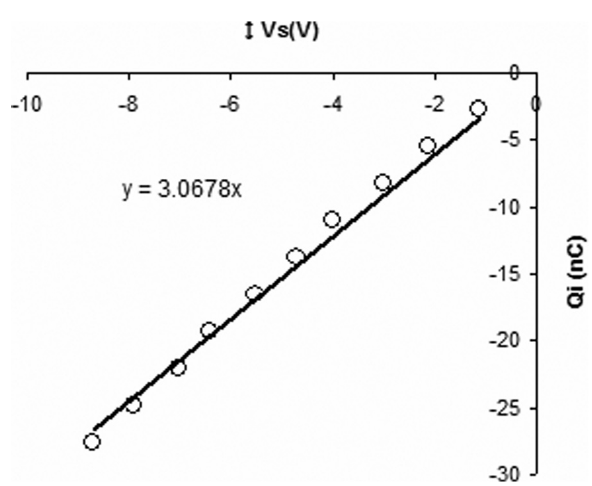

FIG. 2. Capacitance measurement of the BN/sample-holder system: surface potential variation as the function of the injected charge. $V_S = +0$ V and $E_i = 5$ eV.

III. RESULTS AND DISCUSSION

The measured total EEY (TEEY) for BN, BNSiO_2, and Al_2O_3 are shown in Fig. 3. A comparison of the values of the

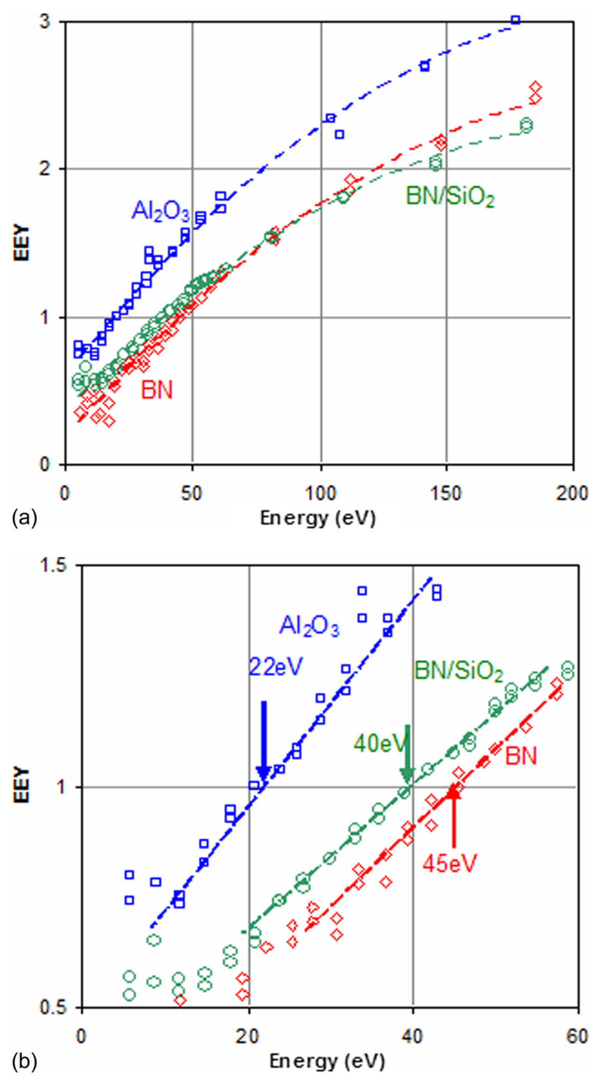

FIG. 3. (Color online) (a) Electron-emission yield for pristine Al_2O_3, BN, and BN/SiO_2. (b) Zoom around the first crossover energy. The lines are guides for the eyes.

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TABLE I. Comparison between the first crossover energies measured in this work and those already published.

Material	Viel-Inguimbert[a]	Dunaevsky *et al.*[b]	This work
BN	30 eV	35 eV	45 eV
$BNSiO_2$	60 eV	—	40 eV
Al_2O_3	18 eV	—	22 eV

[a]Reference 14.
[b]Reference 15.

first critical energy measured in this study with those measured in other studies is given in Table I. E_{C1} was found to be quite different from that already measured. For instance, Viel-Inguimbert[14] and Dunaevsky *et al.*[15] reported $E_{C1} = 30$ eV and 35 eV for BN, respectively, whereas our measurements indicate that $E_{C1} = 50$ eV. This disagreement is not really surprising. Indeed, the secondary electron escape depth is of the order of a few nm, thereby, the EEY is extremely dependent on the physical chemistry of the surface and its microstructure. It is therefore likely that the treatment applied to the surface before irradiation (polishing, chemical cleaning,[15] heat treatment,[20] as well as contamination induced by irradiation[21]) affect significantly the electron emission process, in particular at low energies.

The effects of sample aging under electron bombardment on the EEY were investigated only for BN and Al_2O_3 samples. In Figs. 4 and 5, the yields of BN and Al_2O_3 are plotted showing their evolution during electron irradiation at 200 eV. The emission yield of BN grows rapidly (typically 0.5 mC/cm^2) with electron dose, whereas that of Al_2O_3 reduces slowly (typically 5 mC/cm^2). As a consequence, the first crossover energy for BN decreases and conversely that of Al_2O_3 increases as shown in Fig. 6. Although Al_2O_3 has a first energy crossover approximately two times lower than that of BN before aging, the first crossover energies of these two materials becomes comparable, and even slightly higher for Al_2O_3 after an electron exposure of 5×10^{-3} C/cm.^{2}

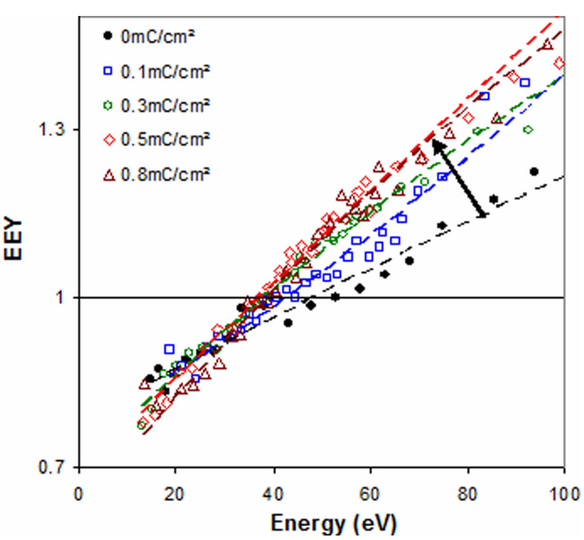

FIG. 4. (Color online) Effect of the electron irradiation (aging) on the TEEY of BN. The lines are guides for the eyes.

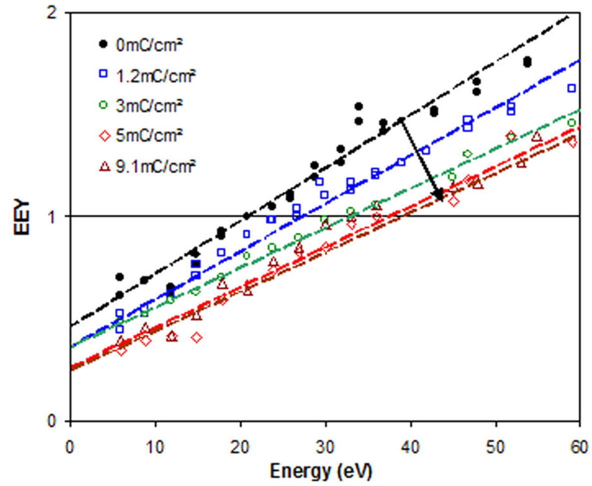

FIG. 5. (Color online) Effect of the electron irradiation (aging) on the TEEY of Al_2O_3. The lines are guides for the eyes.

Two possible mechanisms may be considered for the EEY changes with electron dose:

(i) electron-beam-induced deposition of hydrocarbon layer (contamination), and
(ii) surface and near-surface composition changes induced by electron irradiation.

An interesting result is shown in Fig. 7: after airing the vacuum chamber for several hours and pumping again, the EEY of the Al_2O_3 increases. It is important to note that a similar experience occurred with BN; no EEY change was observed. So, the more likely explanation of the aging effects on the EEY variation for Al_2O_3 is electron-induced surface composition change. Indeed, most surfaces of oxides are not stable under irradiation with ionizing particles, but decompose with a loss of oxygen.[22] In particular, Al_2O_3 reduction to aluminum in a metallic state under electron irradiation is a well-known phenomenon and was already observed.[23,24] This phenomenon is expected to be enhanced at low incident electron energies. Referring to the literature,[25] electron-induced nitrogen desorption from BN was only expected and observed at higher temperatures (typically 900 K–1100 K).

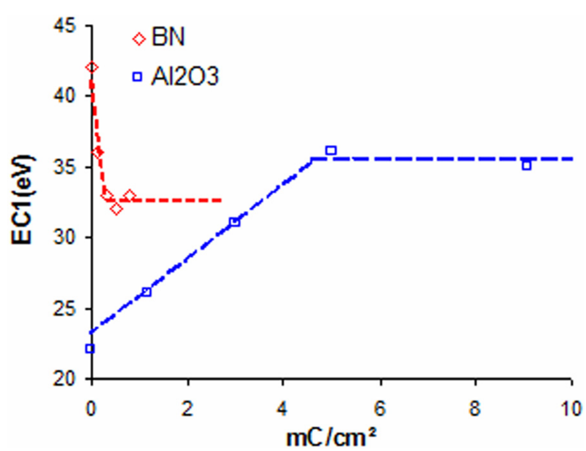

FIG. 6. (Color online) Effect of the electron irradiation (aging) on the first crossover energy of Al_2O_3 and BN.

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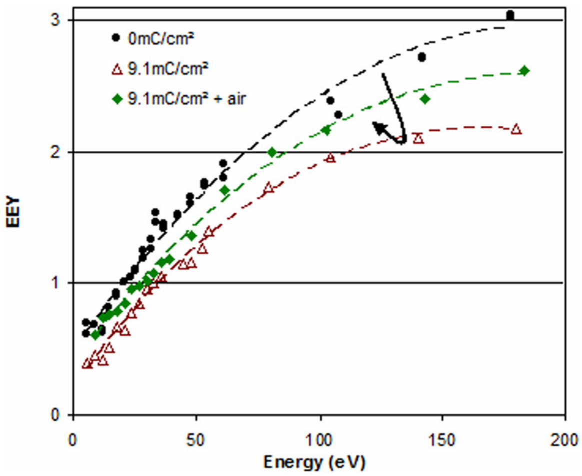

FIG. 7. (Color online) Effect of the air exposure on the EEY of Al_2O_3. The lines are guides for the eyes.

However, our measurements (decrease of E_{C1} with electron dose) highly suggest that electron-beam-induced surface modifications arise during irradiation at room temperature. The investigation on the origin of these surface modifications is out of the scope of this paper.

III. PRACTICAL CONSEQUENCES

Keeping in mind that the current density used in the experiment on the ceramic of HET (1 A/cm^2 or more[26]) is six orders of magnitude higher than that used in this experiment (~10 μA/cm^2), and knowing that electron-induced composition change is enhanced by:

(i) decreasing the incident electron energy,[27] and
(ii) increasing the temperature,[26]

the aging effects on the EEY should be reinforced in the ceramic irradiated with electrons of only several tens of volts and heated to a temperature of 800 K–1100 K. In addition to the effects of the electron irradiation, ion erosion continuously modifies the surface and near-surface composition and topography. As the EEY highly depends both on the surface roughness[28,29] and the chemical composition, obviously the secondary emission evolves during the life of HET. Thus, if a low secondary electron yield material is required for optimal thruster operation, as was suggested,[6–9] selecting ceramic materials on the bases of their "as received" EEY is probably not the best strategy. Accordingly, the question that seems to be the most relevant is rather which material is likely to preserve a low EEY or, better, to decrease it throughout thruster life.

IV. CONCLUSION

Measurements of electron-emission yield of several materials of HET interest have been done. We have shown that the EEY and, in particular, the first crossover energy change when the material is exposed to an electron dose of a few mC/cm^2. This change was attributed to surface and/or near-surface composition change induced by the electron irradiation. The first crossover energy is a key parameter in a number of HET simulation models. This parameter is usually extracted from measurements performed on pristine samples. Our results highlight that the EEY measured on channel material that had not endured the specific HET environment could be very different from that of the same material under HET operation. To be somewhat more representative, the EEY must be measured on materials that have been aged under both ion and electron irradiation. This particular work is in progress.

ACKNOWLEDGMENTS

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