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# Temperature effect on the electron emission and charging of BN–$SiO_2$ under low energy electron irradiation

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ABSTRACT

The BN–$SiO_2$ is widely used as canal material in Hall Effect Thrusters. The electron emission yield under electron impact is considered as a key material parameter that affects the thrust efficiency. The effect of the temperature on the electron emission yield of BN–$SiO_2$ was investigated. It is found that, the electron emission drop significantly when the temperature is increased from 22 °C to 800 °C. The aim here is to report our experimental results and to discuss the representativeness of electron emission data measured on ceramics at room temperature.

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## 1. Introduction

Hall Effect Thrusters (HET) allows 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 canal. 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 canal ceramics. A number of physical models and observations link the limitation of the energetic efficiency of the HET to the electron emission yield (EEY) of canal material [1,2]. BN–$SiO_2$ ceramics is widely used as canal material. The EEY is defined as the ratio of emitted electron number (backscattered (BSE) and secondary electrons (SE)) to the incident electron number. According to HET models, the lower the EEY of the canal material, the higher the maximum attainable electron temperature. 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). To our knowledge, only EEY measurements at room temperature on BN–$SiO_2$ were reported [3–5] . However, the temperature of canal materials under operation is about 500 °C and can reach 800 °C in some specific situations. Previous work on MgO [6] reported a decrease on the EEY as function of the temperature. This is explained by the reduction of the mean escape depth of SE due to the increase of phonon–electron interaction frequency. Therefore, it is important to evaluate the effect of the temperature on the EEY of the HET canal material. Measurement of EEY on dielectrics is known to be difficult because the charge trapping in the ceramics affects the emission yield itself. In this work, a special experimental protocol was established in order to assess the effect of charging on the EEY measurement. Prior the EEY measurement, the effect of the elevation of the temperature on the charging and discharging level of the BN–$SiO_2$ was studied. The elevation of the temperature leads to significant increase of charge carrier mobility. Indeed, at 300 °C, the electrical discharging kinetic becomes fast enough to adequately measure the EEY using a pulsed electron beam. We measured the EEY of BN–$SiO_2$ at temperatures ranging from 300 °C to 890 °C and for incident energies comprised between 10 eV and 100 eV. It was found that the temperature affects significantly the EEY. An overall decrease of the yield as function of the temperature is observed. In particular, the first crossover energy increases from its nominal value (of about 40 eV [5]) to about 80 eV at 612 °C and higher than 100 eV at 816 °C.

## 2. Experimental

The facility used for EEY measurement is equipped with Kimpball physics electron guns: ELG-2 (1 eV–2 keV). The sample is mounted on a holder which the temperature can be varied from

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room temperature to 1000 °C. A hemispherical electron-collecting electrode (collector) faces the sample surface. The electron beam incidence is set normal to the sample surface. The primary beam current is measured with Faraday cup. Short electron pulses were used to minimize the effects of charging. The incident charge fluency per current pulse varies with the primary beam energy and can be set from few fC/mm$^2$ to few pC/mm$^2$. The charging behavior of the sample was investigated in a facility [7] equipped with a Kimball 20 keV electron gun and faraday cups. The sample is mounted on a holder which the temperature can be varied from room temperature to 450 °C. The surface potential of the sample was measured with a Kelvin probe. The studied sample is BN–$SiO_2$ (grade: 60% h–BN, 40% fused silica). The sample is a disc of 20-mm diameter and 2-mm thickness.

Measurement of the EEY of dielectrics is difficult due to the charging effect. Indeed, under irradiation electrons and holes can be accumulated on the dielectric. The charge accumulation at the surface and on the interaction volume may reduce the secondary electron emission by two distinct ways:

- Internally, by acting on the secondary electrons transport inside the target [8–10].
- Externally, by recalling the emitted secondary electrons and freezing the emission of the SE with the lowest energies [8,11].

Many methods were developed to discharge the sample between two electron pulses (UV photons, electron beam, heating ...) [12–14]. In this work the sample heating technics was preferred because it meets two objectives: (i) working at temperatures representative of the ceramics of the HET under operation and (ii) increasing the discharging kinetics. BN–$SiO_2$ and $Al_2O_3$ ($Al_2O_3$ was placed on the same sample-holder for comparison) were negatively charged with e-gun energy of 15 keV and incident current density of 1 nA/cm$^2$, at different temperatures (room temperature, 150 °C and 300 °C). Fig. 1, shows the surface potential profiles measured along the axes of the both samples during the irradiation. 20 profiles were measured at each given sample holder temperature. After 18.5 min of electron irradiation, the surface potential of BN–$SiO_2$ reaches −1.22 kV at room temperature (22 °C) and only −0.46 keV at 150 °C. At 300 °C and at 400 °C, no significant charge was observed. Indeed, at 300 °C, the charge carrier mobility was increased enough so that the excess of injected charges under irradiation are efficiently dissipated. This result implies that the measurement of the electron emission yield with the help of the conventional current method is applicable at 300 °C and at higher temperature providing that the electrons pulses are short (few tens of μs). During the electron pulse irradiation the collector current was recorded. The hemispherical collector is biased to +36 V with respect to the sample surface in order to extract all emitted electrons by the sample and also to recapture those which are emitted by the collector itself. Only a small fraction of backscattered electrons can escape. Prior to the measurements, the incident beam pulse current is measured with a help of a Faraday cup placed at output electron-gun diaphragm. The methods as wells the calibration procure is described in ref [15]. The EEY yield is thereafter deduced from the following equation:

$$\mathrm{EEY} = \frac{I_C}{I_F} \tag{1}$$

## 3. Results

Before the EEY measurements the sample was heated under high vacuum conditions (in the range of $10^{-8}$ mbar) at 470 °C during several hours for degassing purpose and thereafter it was cooled to room temperature. The measured EEY of BN–$SiO_2$ at 300 °C, 612 °C, 816 °C, 816 °C and 892 °C for BN–$SiO_2$ are compared to that measured in our previous work [5] at room temperature on Fig. 2. The elevation of temperature leads to an overall decrease of the EEY. The first crossover energy shifts from its nominal value of 40 eV at room temperature to 68 eV at 400 °C. The obtained results on BN–$SiO_2$ are not really unexpected or surprising. Indeed, many years ago Johnson and Mc Kay [6] have observed a similar temperature effect on MgO. The maximum electron emission yield decreased when the temperature is increased from room temperature to 740 °C. The result was attributed to the interaction of the SEs undergoing emission with the lattice vibration (phonons). Indeed, the elevation of the temperature increases the electron–phonons interaction frequency, resulting in the decrease of the free mean path of the inner SE. One other temperature effect that leads to the decrease of the EEY of "exposed to atmosphere" materials is a surface cleaning process. Indeed, the surface of any sample which has been subjected to air exposure (even very short time) is contaminated manly by hydrocarbon species. A contamination layer of few nm remains on the sample surface even after exposition to ultra-high vacuum conditions during weeks. However, when the temperature is increased, some contaminants are desorbed from the surface leading to an overall and significant decrease of the EEY. This well-known effect was observed on many metals [16,17].

## 4. Discussion

In previous work we have shown that the EEY of BN–$SiO_2$ is sensitive to the electron irradiation [5]. A few mC/cm$^2$ irradiation leads to a substantial increase of the first crossover energy. We show here, that the temperature also affects the EEY of BN–$SiO_2$. Keeping in mind that:

- The temperature of the ceramic of HET is in 500 °C range or higher in some situations.
- The electron current density impacting the HET ceramics is many orders of magnitudes higher than that commonly used on secondary electron experiments.

The ion erosion and the contamination continuously modify the surface and near surface composition and topography.

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 it was established, selecting ceramic materials on the bases of their "as received" EEY measured at room temperature 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 all lifelong of the thruster and under high temperatures. Tuning the chemical composition of the canal material in order to reduce its EEY at room temperature is likely to be a wasted effort because the composition of its surface will probably change quickly (first seconds) after the ignition of the thruster. For a long-term electron emission reduction, the use of canal materials with rough surfaces could be a better approach. Indeed, at low incident electron energy (typically that encountered in HET canal, few to tens eV), roughness always decreases the EEY. This is due to the fact that the main effect of roughness at low incident electron energies is the decrease of the effective emission solid angle. Accordingly, more important the roughness, lower the EEY. The efficiency of this EEY reduction strategy is however conditioned by maintaining a significant roughness, despite the permanent ion bombardment of the surface during the HET life. This is what maybe happens when composite ceramics (e.g. BN–$SiO_2$) are used. In recent work [18] it was shown that the roughness and the chemical composition of the surface canal material (BN–$SiO_2$) evolves dramatically

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