Secondary Electron Emission Properties of Boron Nitride Ceramic Materials at High Temperatures

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Secondary electron yield measurements as a function of temperature are presented for Boron Nitride (BN) of grades HP, AX05, and M26. The energy at which the yield equals to 1 ($\boldsymbol{E_1}$) at room temperature was measured to be near 40 V for all three grades. At an elevated temperature of 320 C the yield was measured to be not significantly different than the yield at room temperature for the grade AX05. The elevated temperature yield for the HP grade was only slightly lower than at the room temperature. The yield of the M26 grade was significantly different at 320 C than at the room temperature, however that difference was smaller than measured by other researchers.

Nomenclature

σ	=	secondary electron emission yield
E_P	=	energy of primary electrons at the sample
I_{PE}	=	primary electron beam current
I_S	=	sample current
I_{SEE}	=	current due to secondary electron emission
U_C	=	collector bias voltage
α, β	=	fitting coefficients

I. Introduction

THERE is reliable experimental evidence of the wall material effect on operation and performance of electric thrusters such as Hall thrusters.[1-3] The existing theories explain this effect by invoking a strong secondary electron emission (SEE) from the thruster channel walls.[2,4] The SEE can greatly alter the plasma-wall interaction and, in turn, the whole structure of the plasma discharge and the plasma stability. The SEE process can be characterized in terms of the SEE yield, which is the ratio of the total emitted secondary electron flux from the wall surface to the primary electron flux to the wall surface and the energy spectrum of emitted electrons. Secondary electrons emitted from a surface bombarded by primary electrons, are commonly divided on two categories: low energy "true" secondary electrons, and inelastically and elastically backscattered electrons with energy spectrum

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from several tens of eV up to the higher energy of primary particles.[5-7] For accurate modeling of plasma-wall interaction, it is important to know the SEE properties, including the SEE yield and its angular dependence, and energy distribution function of emitted electrons, in the range of the electron temperature in the plasma. For electric thrusters, such as Hall thrusters, FRC, and rf-plasma thrusters (e.g. helicon, ECR etc), this range is from a few eV to a few hundreds of eV. There is no systematic data on secondary electron emission in this energy range for most modern ceramic materials used in electric thrusters. Existing theories of SEE from dielectric materials are mostly semi-empirical and have no reliable predictive capabilities.[6-8] Furthermore, during the thruster operation, including the thruster startup transient,[9-10] heating of the wall to 300-600 C (See, for example, in Ref. 11) and plasma-induced modifications of the wall surface may alter the SEE properties of the wall material causing changes of the thruster operation stability of the thruster discharge and potentially, thruster performance.

Several works reported measurements of the SEE yield for ceramic materials relevant to Hall thrusters.[12-15] Refs. 12-15 showed that SEE properties can be affected by the sample temperature and the electron current. In particular, measurements of the SEE yield from a boron nitride ceramic grade M26 showed that the SEE yield decreases as the sample is heated from the room temperature to 300-400 C. This result was attributed to the increase of scattering of the secondary electrons due to enhanced electron-phonon interaction at elevated temperatures.[14] In this work, we summarize the temperature effect on the SEE yield from three different boron nitride (BN) ceramic materials manufactured by Saint Gobain, including high purity BN of grade AX05, BN grade HP with an addition of calcium, and grade M26 composed of boron nitride and silica.[16] A more detail analysis of these results will be reported in a separate paper.

II. Experimental Setup and Measurement Procedure

The experiments were conducted in the Surface Science and Technology Laboratory (SSTL) at the Princeton Plasma Physics Laboratory. The SEE apparatus is equipped with two electron gun-measurement systems based on the LEED/Auger electron gun optics and Kimbal Physics electron gun, respectively. Both systems are installed in the same vacuum chamber which is equipped with a turbo pump and an ion pump. A typical base pressure in the vacuum chamber does not exceed 10^{-8} Torr. However, in the experiments described in this paper, the background pressure could be as high as 10^{-7} Torr during the SEE measurements for the heated ceramic samples. In Ref. 5, we showed that the SEE measurements are not very sensitive to the change of the pressure in this range.

For measurements from the conductive materials, a PHI model 15-120 LEED/AES optics consisting of an electron gun capable of producing a monoenergetic electron beam with an energy between 3 and 1600 eV, four hemispherical semitransparent grids (the first with 120° solid angle), and a final hemispherical phosphor-coated solid screen, is used.[5] For measurements from the dielectric materials, including measurements described in this paper, we use an electron gun and a collector arrangement described in Ref. 12. This arrangement is represented schematically in Fig. 1. The primary electron beam was generated by an electron gun ELG-2 produced by Kimball Physics, Inc. The range of the electron energies was 10–200 eV. In order to minimize the influence of the surface charging of the dielectric samples, the primary electron beam was modulated by short pulses of up to few microseconds, as was described in Ref. 12. The duration of the pulse was set by an external 6040 pulse generator produced by Berkeley Nucleonics Corp. The maximum beam current did not exceed 200 nA. Following the recommendations of Ref. 12, in order to minimize the surface potential, the focal spot radius of the beam on the sample was maintained ~1 mm. The decrease of the focal spot allowed the increase the time constant of the measuring circuit, RC, which is required to be higher than the pulse duration, and to decrease the influence of the parasitic capacitances. Charging effects were additionally mitigated by changing the beam spot on the sample and by heating the sample.[12.] This procedure does not provide a complete removal of the surface charge, which is accumulated inside the material to

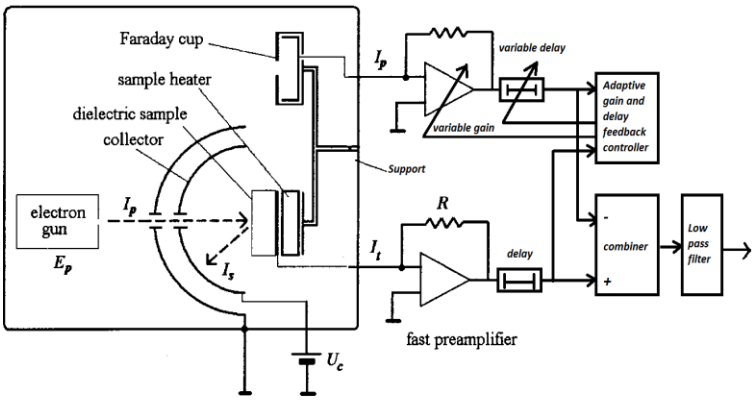


Figure 1.Upgraded setup for low noise and high resolution measurements of the SEE yield from the dielectric materials.

the depth of several monolayers. However, repetitive measurements at the same primary energy showed the deviation of the SEE yield to be less than 10%.

In our experiments, boron nitride samples were mounted on a sample holder made of boron nitride. The parasitic capacitance between the rear sample electrode and the ground was minimized to 1.5 pF. The sample holder was attached to the high vacuum sample heater produced by HeatWave Corp. The temperature of the samples was initially monitored only by a K-type thermocouple embedded into the sample holder by the manufacturer. However, during experiments, it was found that the surface temperature can be significantly different than the embedded thermocouple indicated. For example, when the thermocouple read 400C the surface temperature was 320C. Subsequently, to improve the accuracy, the surface temperature was also measured with a K-type thermocouple attached to the BN samples.

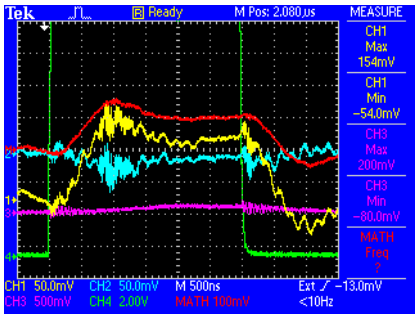
The sample holder was mounted on a rotating stage, together with a Faraday cup for measurements of the primary electron beam current, I_{PE} (see Fig. 1). The potential of the collector, U_C , was selected in the range of 10–100 V depending on the current saturation for each material and energy of the primary electrons, E_P.[5]

Prior to measurements, the sample surface exposed to the electron beam was cleaned by mechanical exfoliation. Measurements were made by exposing a sample of the material to a monoenergetic electron beam of known current I_{PE} and measuring (i) the sample current I_S or (ii) the current on a collecting electrode surrounding the sample I_C.[5] The total yield σ is then

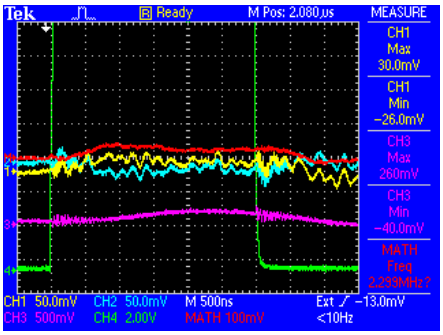
$$\sigma = \frac{I_{SEE}}{I_{PE}} = \frac{I_{PE}-(I_{PE}-I_{SEE})}{I_{PE}} = \frac{I_{PE}-I_S}{I_{PE}} = 1 - \frac{I_S}{I_{PE}} \quad (1)$$

The current measurement system and the procedure were modified compared to Ref. 12 in order to increase the sensitivity and improve the accuracy of the measurements by reducing the signal-to-noise of the measured signal. The signal from the sample and from the Faraday cup were amplified by directly coupled fast amplifiers with bandwidth of 10 MHz, gain slightly exceeding 100 V/A, and the current resolution of 2 nA. Amplified signals were then digitized and delayed. Moreover, the amplitude and the delay of the Faraday cup channel are variable and constantly controlled by the adaptive gain and delay controlled even when the beam is not exposed to the cup, but to the sample. Then, in the combiner (see Fig. 1), the time and the amplitude aligned signal from the Faraday cup were subtracted from the sample signal to compensate for ambient noise in the system during the pulse. Such a dual channel processing allowed minimizing of the sample surface charging by keeping the primary electron beam current pulse amplitude at the ambient electromagnetic noise level and, at the same time, keeping the bandwidth of each channel wide to shorten the current pulse duration down to 1 microsecond. Fig. 2 illustrates this measurement and noise compensating procedure for three energy ranges corresponding to the SEE yield below 1, nearly 1 and above 1. The yellow trace in each graph is the sample current, magenta trace is the Faraday cup signal, and red trace is the processed waveform. As can be seen the output signal of the combiner at different energies was mostly free of non - time stationary noise components. The obtained signal contains only

a)



b)



c)

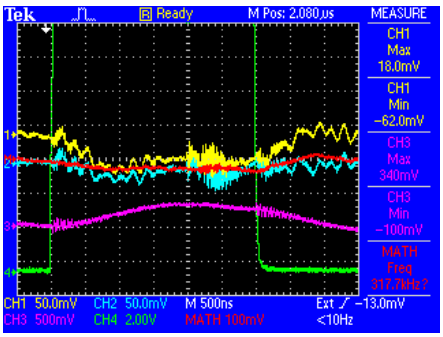


Figure 2. SEE measurements for a BN sample: sample current signal (yellow), Faraday cup (references) signal (magenta), and the processed waveform (red) at beam energy of a) 20eV, b) 50 eV and c) 70 eV. The SEE yield estimated using the sample method (Eq. 1); a) less than 1, b) about 1; and c) more than 1.

remaining white Gaussian non-correlated noise components which were further filtered with low-pass and median filters.

III. Experimental Results

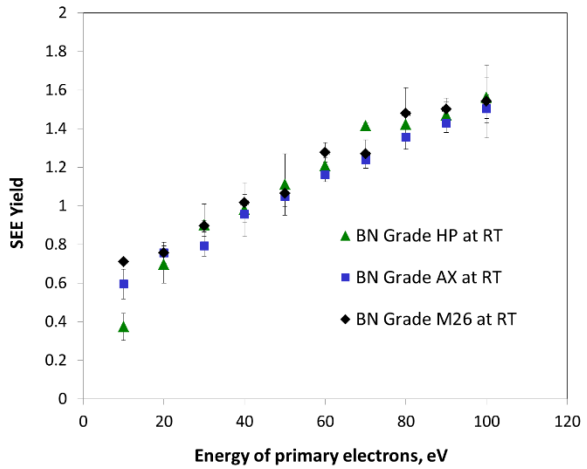


Figure 3. SEE yield for boron nitride grades HP, AX05 and M26 at room temperature.

Fig. 3 compares the SEE yield as a function of the primary electron energy measured for different BN ceramic materials at room temperature. According to these measurements, the differences between the SEE yield for grades AX05, HP, and M26 are generally within the statistical uncertainty of these measurements.

Fig. 4 and Table 1 show the effect of the sample temperature on the SEE yield from different BN ceramic materials. Table 1 shows parameters for two types of fits, which are typically used for the BN SEE yield.[17,18] Fig. 4b and 4c show that for the samples at room temperature, the measured results for BN grades HP and M26 are generally comparable with the results of previous measurements reported in Ref. 12 and 14, respectively. However, the effect of the sample temperature on the SEE yield is not nearly as strong as reported in Ref. 14 for BN grade M-26 (Fig. 4c). This small change of the yield with the sample temperature was reproducible.

The contradiction between our measurement results and the results of Ref. 14 is not understood at the moment. In spite of the care taken to minimize the charging effects in our experiments and seemingly reproducible measurement results, we did not monitor charging, while in Ref. 14, it was monitored using Kelvin probe. Another possible explanation of this difference is that in our measurements, the sample method was used for all ceramic materials at room temperature and the elevated temperature. In Ref. 14, the SEE measurements for cold sample were taken using the sample method as well, but for moderate temperatures, the yield was

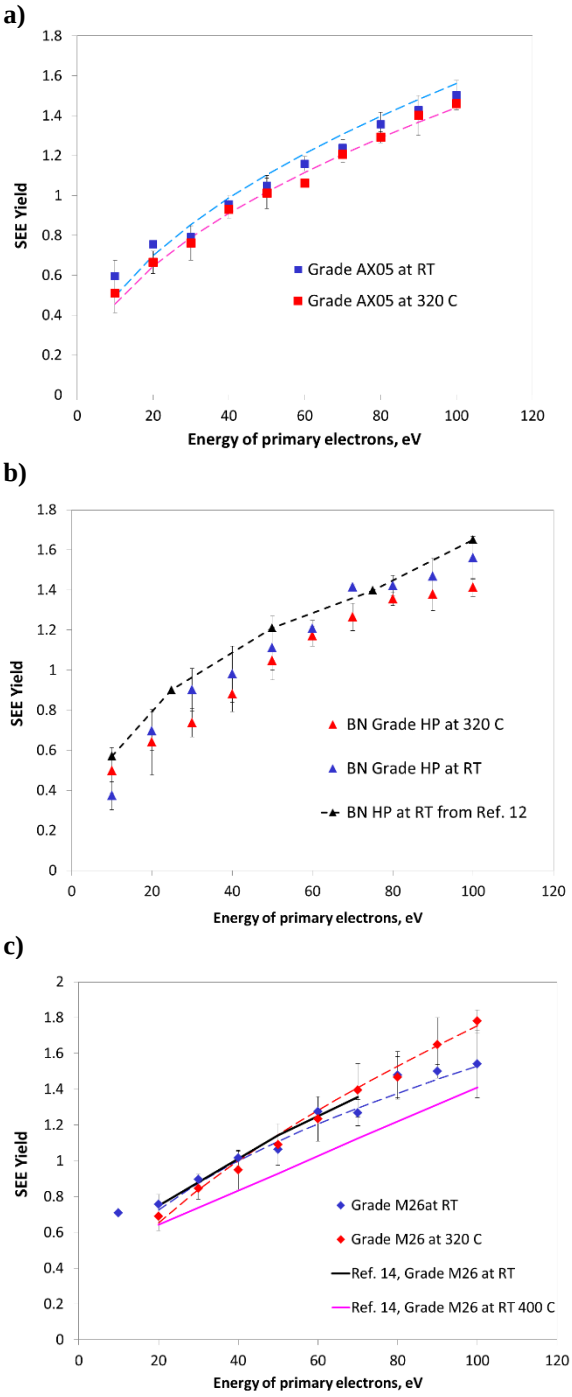


Figure 4. SEE yield for BN grades at room temperature and 320 C: a) Grade AX05; b) Grade HP, and c) Grade M26. In addition, data from other SEE measurements for BN HP (Ref. 12) and M26 (Ref. 14) are shown on Figure b and c, respectively. Dashed lines on figures a) and c) are for Fit 1 and Fit 2 (see Table 1), respectively.

measured using a collector method.[14] In this method, the SEE yield is determined as the ratio of the sample current to the collector current.[5] Finally, we note measurements reported in this paper were taken at a pressure at least 10 times lower than the background pressure in Ref. 14. A more detail analysis of the measurements results and their comparison with other measurements will be presented in a separate paper.

Table 1. Parameters for two fits of SEE yield, σ(Ep), for different boron nitride ceramics of different grades at room temperature (RT) and 320 C.

FIT:	Fit 1 from Ref. 17 $\sigma(Ep) = \alpha E_p^{0.5}$		Fit 2 from Ref. 18 $\sigma(Ep) = (E_p/E_1)^{\beta}$	
Temperature	**α at** RT	**α at** 320C	**β at** RT	**β at** 320C
BN Grade AX05	0.156	0.144	0.424	0.396
BN Grade HP	0.155	0.167	0.463	0.613
BN Grade M26	0.166	0.148	0.589	0.408

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