Total Electron Emission Yield of electric propulsion materials

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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, SiO_2, BN-SiO_2 and Al_2O_3. The effects of the material ageing (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 decreases. A simple analysis of our experimental results indicates that these variations are most likely due to surface and near surface composition changes caused by the electron beam. The impact of implanted electrical charges during electron bombardment is also discussed. The representativeness of EEY measurements on ceramics which have not suffered from the specific environment of a HET (ion and electron bombardment) is discussed.

Nomenclature

C	=	Electrical capacitance
V_S	=	Sample surface voltage
E	=	Energy
EEY	=	Electron emission yield

I. 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 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.

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According to these models, the lower the EEY of the channel material, the higher the maximum attainable electron temperature. In order to improve hall thrusters capabilities for deep space missions, efforts are being done to push the limits of each component of material. 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 to 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 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 were 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, SiO_2 and BN-SiO_2) used as ceramic channel materials are presented. The interest is also focused on exploring the effects of ageing under electron irradiation on the EEY than on the yield measurement itself. The representativeness of EEY measured on materials which 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

Four ceramics were analyzed: BN (h-BN, hot pressed sintering), BN-SiO_2 (Saint-Gobain, M26 grade: 60% h-BN, 40% fused silica), SiO_2 (optical grade fuse silica) and Al_2O_3 (purity>99.7%). The samples are discs of 20 mm in diameter and 2 mm in thick. 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 to oil-free molecular-diaphragm pumps. The sample is mounted in a holder which 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 trough a Femto-DHPCA-100 high speed and a low noise current amplifier. ELG2 Kimball instrument electron gun (3 eV- 2000 eV) with a µs electron beam pulsing capacities was used as the electron source. The sample surface could be measured with high-sensitivity (3 mV) Trek-6000B-15C Kelvin probe, connected to Trek-323 electrostatic voltmeter. All the measurements are performed at room temperature.

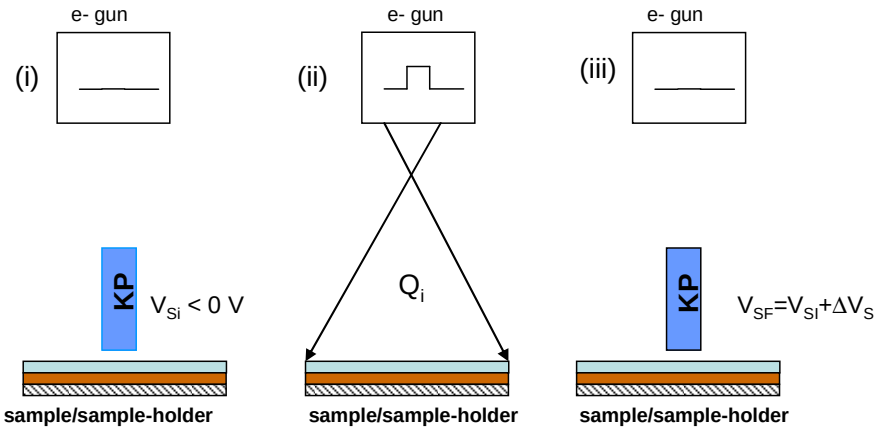

Figure 1. The three steps of the electron emission yield measurement with the KP method

The Kelvin probe (KP) method[13,16] is a three steps method (see figure 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 Qi. In the third step (iii), the KP is repositioned in front of the sample surface in order to measure the new value of the surface

potential, V_{Sf} . The surface potential variation $\Delta V_S = (V_{Sf}-V_{Si})$ can be either positive or negative depending if the EEY is greater or lower than one. Pulse fluence is adjusted to limit ΔV_S within the range -2V to +2V. 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 one eV.

A 50 µm of kapton is introduced between the rear sample surface and the sample holder in order to prevent a 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)

$$EEY = 1 - \frac{C\Delta V_S}{Qi} \quad (1)$$

Between two electron pulses the sample is discharged. This is achieved by alternating short electron pulses where EEY<1 when the sample is positively charged and where EEY>1 when the sample is negatively charged.[17-19] Note that the "as received" ceramics are usually charged before being exposed to electron beam 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-SiO2 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. Due to 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 slop of *Qi* versus ΔV_S characteristic shown in figure 2. For instance, *C* is found to be 3.2 pF for BN/sample-holder system.

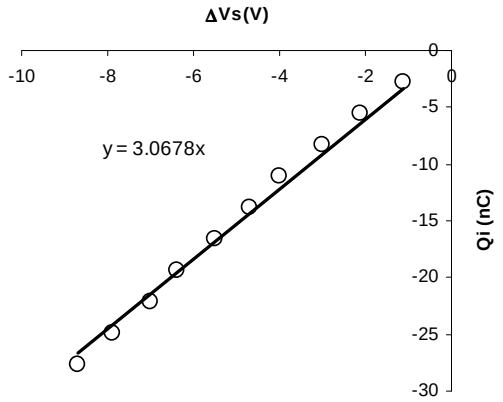

Figure 2. capacitance measurement of the BN/sample holder system: surface potential variation as the function of the injected charge. V_S = + 0 V and E_i= 5 eV.

III. Results and discussions

The measured TEEY for SiO_2, BN, $BNSiO_2$ and Al_2O_3 are shown in figure 3. A comparison of the values of the first critical energy measured in this study with those measured in other studies is given in table 1. E_{C1} was found to be quite different from that already measured. For instance Viel-Inguimbert[14] and Dunaevsky et al. [15] reported respectively E_{C1} = 30 eV and 35 eV for BN, whereas our measurements indicate that E_{C1} = 50 eV. This disagreement is not totally surprising. Indeed, the secondary electron escape depth is of the order of 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. BN appears to be the material with the highest first cross over energy and SiO_2 to have the lowest one. BN/SiO_2, compose of BN and SiO_2 seems to be much more influenced by BN than by SiO_2.

Table 1: Comparison between the first crossover energies measured in this work and those already published.

Material	Ref. 14	Ref. 15	This work
BN	30 eV	35 eV	45 eV
SiO_2	50 eV	35eV	15eV
$BNSiO_2$	60 eV	/	40 eV
Al_2O_3	18 eV	/	22 eV

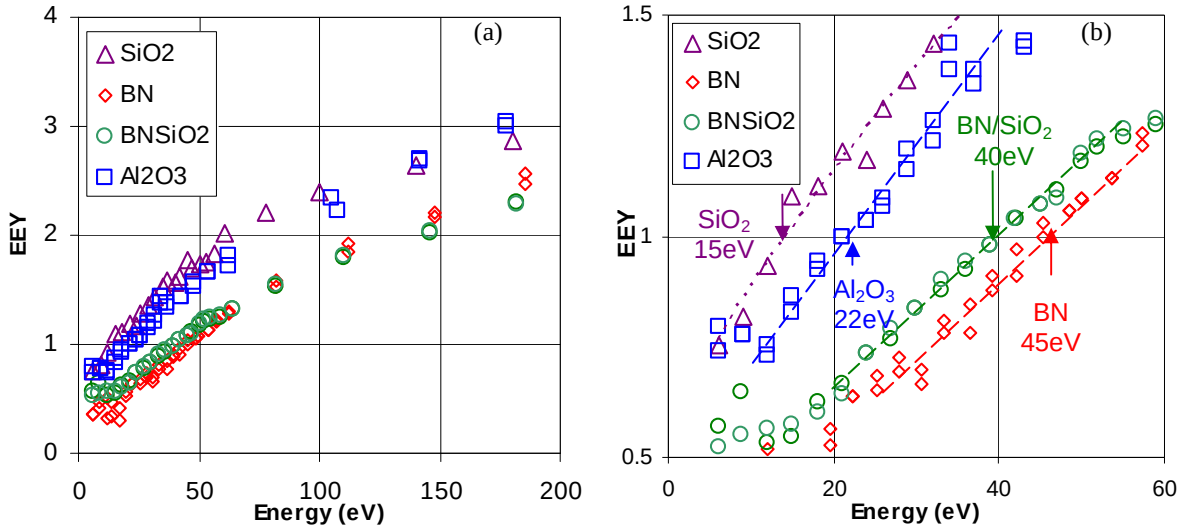

Figure 3: (a) Electron emission yield for pristine SiO_2, Al_2O_3, BN and BN/SiO_2. (b) Zoom around the first crossover energy. The lines are only a guide for eyes

It also appears that the notion of electron emission yield depends on irradiation conditions. The effects of sample ageing under electron bombardment on the EEY were investigated only for BN and Al_2O_3 samples. In figures 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 0.5mC/cm²) with electron dose, whereas that of Al_2O_3 reduces slowly (typically 5mC/cm²). As a consequence, the first crossover energy for BN decreases and conversely that of Al_2O_3 increases as it is shown in figure 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 /cm².

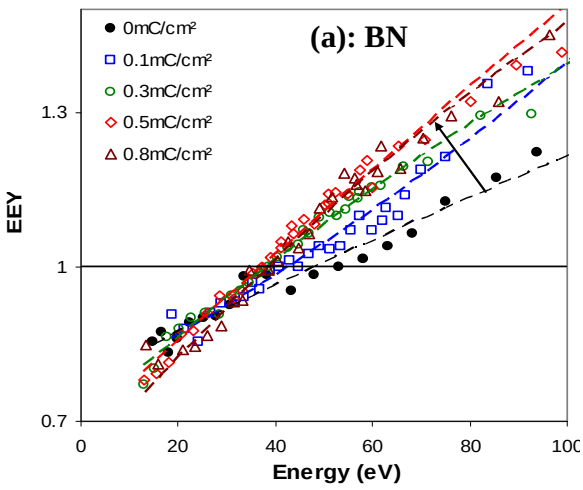

Figure 4: Effect of the electron irradiation (ageing) on the TEEY of BN. The lines are only a guide for eyes

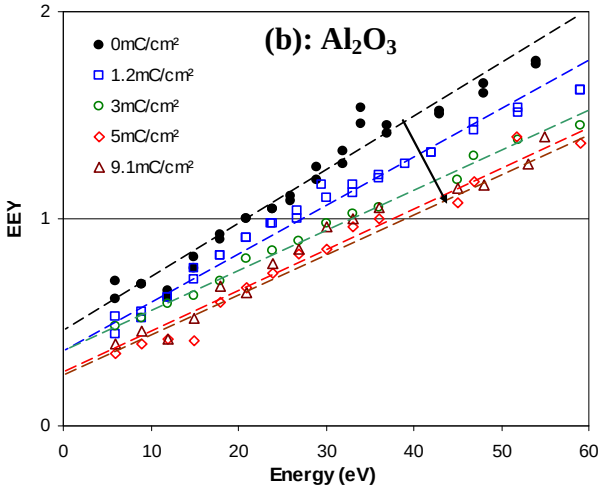

Figure 5: Effect of the electron irradiation (ageing) on the TEEY of Al2O3. The lines are only a guide for eyes

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

(i) electron beam induced deposition of hydrocarbon layer (contamination);

(ii) surface and near surface composition changes due to induced by electron irradiation.

Interesting result is shown in figure 7: after airing the vacuum chamber during several hours and pumping again, the EEY of the Al_2O_3 increases. It is important to note that similar experience was made 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 aluminium in 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). However, our measurements (decrease of E_{C1} with electron dose) highly suggest that electron beam induced surface modifications arise during the irradiation at room temperature. The investigation on the origin of these surface modifications is out of the scoop of this paper.

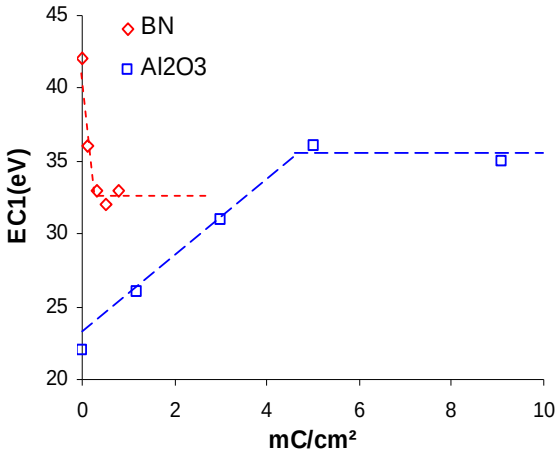

Figure 6: Effect of the electron irradiation (aging) on the first crossover energy of Al_2O_3 and BN.

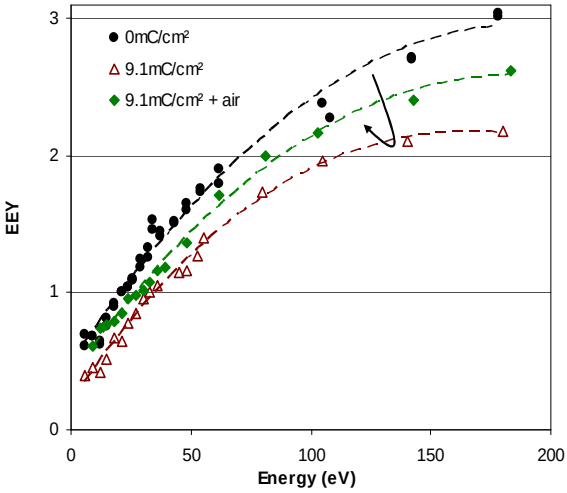

Figure 7: Effect of the air exposure on the EEY of Al_2O_3. The lines are only a guide for eyes

On the studied materials, electron current density effects have not been observed (in the 1 to 100nA/cm² range), while it can be observed in other materials in which charge carriers have a higher mobility. This effect could be observed at higher electron current (more representative to HET) or at higher temperature since charge carrier mobility is increased by temperature.[26]

In opposition it appeared that trapped charges effects[10-12] can be measured.[27] Figure 8 shows the evolution of the EEY of silica due to charges implantation. These measurements were obtained by the KP method by incremental irradiation, where the surface potential was systematically kept slightly negative by adjustment of the control electrode voltage. Figure 8 presents the variations of the EEY at 85eV and 1200eV. The accumulated charges are expressed in total surface voltage build up due to positive charges accumulation.

These EEY variations are explained as a consequence of trapped charges on the electronic cascade induced by electron bombardment.

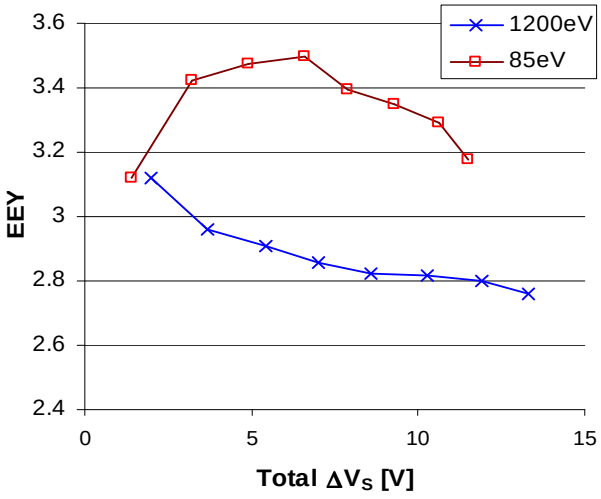

Figure 8. Influence of the accumulated charges (and resulting potential build up) on the electron emission yield.

IV. Practical consequences

Keeping in mind that the current density experimented by the ceramic of HET (1 A/cm² or more[28]) is six orders of magnitude higher than that used in this experiment (~10µA/cm²) and knowing that electron induces composition changes is enhanced with:

(i) decreasing the incident electron energy[29] and
(ii) increasing the temperature[28],

the ageing 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 800K-1100K. 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[30,31] 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 it 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 all life long of the thruster.

Furthermore, electron emission under electron impact depends on electrical charges implanted in target materials. The practical consequence is that in addition to electrostatic effects, the electron emission yield will depend on the accumulated charges in the ceramic material. This accumulation is a function of the creation rate (irradiation current) and of the relaxation term (diffusion and conductivity) that depends on ceramic temperature.

V. Conclusion

Measurements of electron emission yield of several materials of HET interest have been done. We have shown that materials exposed to electron bombardment evolve so that the EEY and in particular the first crossover energy change when the material is exposed to electron dose of few mC/cm². This change was attributed to surface and/or near surface composition change induced by the electron irradiation. In addition, the amount of implanted charge also influence the electron emission yield, so that in a HET, the EEY depends on the wall equilibrium potential. 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 that are hopped to be free from charges. Our results highlight that the EEY measured on channel material that have not endured the specific HET environment could be very different from that of the same material under HET working. To be somewhat more representative, the EEY must be measured on materials that have been aged under both ion and electron irradiation. The work is in progress in this way.

Acknowledgments

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References

[1] I. Bugrova, A. V. Desyatkov, A. I. Morozov, and V. K. Kharchenikov, Plasma Phys. Rep. 4, 302 (1996)

[2] J. Ashkenazy, Y. Raitses, and G. Appelbaum, Phys. Plasmas 5, 2055 (1998)

[3] N. Gascon, M. Dudeck and S. Barral , Phys. Plasmas 10, 4123 (2003)

[4] Y. Raitses, A. Smirnov, D. stack and N. J. Fish, Phys of Plasma 13 (2006) 014502

[5] S. Mazouffre, K. Dannenmayer J. Appl. Phys. 102, 023304 (2007)

[6] G. D. Hobbs and J. A. Wesson, Plasma. Phys. 9, (1967) 85

[7] M. Keidar, I. D. Boyd and I. I. Beilis, Phys. Plasma 8, (2001) 5315

[8] S. Baral, K. Makowski, Z. Peraadzynski, N. Gascon and M. Dudeck Phys. Plasma 10 (2003) 4123.

[9] E. Ahedo, Phys. Plasmas 9, (2002) 4340.

[10] Cazaux J 1999 *J. Appl. Phys.* **85** 1137,

[11] Deninison J R, Sim A and Thomson C D 2006 *IEEE Tran. Plasma Science* **34** 2204,

[12] M. Belhaj, Th, Tondu, V. Inguimbert, Appl. Surf. Sci. 10.1016/j.apsusc.2010.12.081

[13] T. Tondu, M. Belhaj and V. Inguimbert J. Vac. Sci; Tech A 28 (2010) 1122

[14] V. Viel-Inguimbert 2003 Proc. of the 28rd Int. Electric Propulsion Conf. IEPC-3 Electric Rocket Propulsion Society, Worthington, p 258

[15] A. Dunaevsky, Y. Raitses and N. J. Fish, Phys, 10 (2003) 2547

[16] M. Belhaj, T. Tondu, V. Inguimbert, J. P. Chardon J. Phys. D: Appl. Phys. (2009) 42,105309

[17] Hopman H J, Alberda H, Attema I, Zeijlemaker H, Verhoeven J 2003 J. Electr Spectoscopy and Related Phenomena 131-132 51

[18] Belhaj, T. Tondu, V. Inguimbert J. Phys. D: Appl. Phys. (2009), 42,145303

[19] G. Blaise, F. Pesty, P. Garoche J. Appl. Phys. 105 (2009) 034101]

[20] Bojko I, Hileret N and Scheuerlein C 2000 *J. Vac. Sci. Technol A* **18** 972

[21] E. I. Rau, Appl. Surf. Sci. 254, 2110 (2008)

[22] Raul A. Baragiola and Theodore E. Madey, Phys Rev. B 41 (1990) 9541

[23] O.V. Rakhovskaya, S.S. Elovikov, E.M. Dubinina, E.S. Shakhurin, A.P. Dementjev, Surface Science 274 (1992) 190

[24] A. Hoffman and P. J. K. Paterson, Appl. Surf. Sci. 93 (1996) 301

[25] S. S. Elovikov, V. E. Yurasova, Yu. A. Ryzhov, S. A. Khartov, I. I. Shkarban, R. S. Gvozdover J. Surf. Invest X-ray Synchotron and Neutron Tech. 2 (2008) 934

[26]M Belhaj, T Tondu, V Inguimbert, Pierre Barroy, François Silva and Alix Gicquel, *J. Phys. D: Appl. Phys.* 43 135303 (2010)

[27]M Belhaj, T Tondu, V Inguimbert Applied Surface Science, 2011, vol. 257, n°10, pp. 4593-4596

[28] Hong Li, Fengkui Zhang, Hui Liu, Daren Yu Phys. Plasmas **17**, 074505 (2010)

[29]L. Calliari, Nucl. Inst. Meth. B 58 (1991) 199

[30] V. Baglin, J. Bojko, O. Gröbner, B. Henrist, N. Hilleret, C. Scheuerlein, M. Taborelli, Proceeding of EPAC 2000, Vienna, Australia

[31] M. Pivi, F. K. King, R. E. Kirby, T. O. Raubenheimer, G. Stupakov, and F. Le Pimpec J. Appl. Phys. **104**, 104904 (2008)]