Electron-induced secondary electron emission coefficient of lithium, tungsten and stainless steel surfaces exposed to low-pressure plasmas

E. Oyarzabal, A.B. Martin-Rojo, F.L. Tabarés

Abstract

The secondary electron emission (SEE) coefficient by electron impact of Li, W and stainless steel (SS) surfaces exposed to a glow discharge is evaluated and analyzed in the energy range of $E_e < 200$ eV. While the values of the SEE coefficient for SS and W show a small increase with respect to their vacuum value, an enhancement of this parameter up to a factor of 6 has been deduced for clean Li surfaces. Experiments with different plasma gas discharges (He, Ar and H_2) are undertaken in order to address the possible mechanisms related to such enhancement. No major effect of the bombarding ion mass or incident electron flux is observed. The implications of these findings on the use of Li as a plasma-facing component in fusion devices are addressed.

1. Introduction

The emission of charged particles from surfaces exposed to fusion plasmas has deep implications for the lifetime of plasma facing components (PFC's) as well as for the plasma edge characteristics, of paramount impact on global plasma confinement [1]. Thus, the ejection of positive ionic species by physical sputtering leads to cleaner plasmas, as compared to the typically dominant ejection of neutrals, due to the intrinsic screening effect that the plasma sheath plays with respect to positive charges [2]. Moreover, the prompt re-deposition of these positive ions, with energies well below the typical magnitude of the sheath potential, $V \sim 3$ kTe, with Te the electron temperature at the last closed flux surface (LCFS), directly contributes to the extended lifetime of the corresponding plasma facing component. This concept led, for example, to the proposal of alkali metals as candidates for PFC's in the early 1980s [2]. On the other hand, the impact of emission of electrons by ion or electron impact is twofold. First, the local sheath, responsible for the acceleration of the ions escaping the plasmas, is modified by the injection of the emitted electrons in the form [3].(1)where $V_f = V_{sheath}$, Te and Ti stand for the plasma electron and ion temperatures, respectively, and δ_e is the SEE coefficient of the material facing the plasma. As δ_e increases to values close to 1, the potential drop between the material and the plasma decreases toward zero (sheath-free conditions), thus opening the possibility of directly measuring the plasma potential, V_p, as exploited by the emissive Langmuir probe diagnostic [4]. Under the sheath-free condition, the energy of the ions hitting the plasma-exposed material is drastically reduced to $2kT_i$, instead of their generally assumed value of $E_i = 2kTi + 3z$kTe, with z being the charge state of the corresponding species. Although the generation of impurities by physical sputtering, directly connected to E_i, would be dramatically reduced under high SEE conditions, the heat load associated to electron bombardment may overcompensate for this beneficial effect [3].(2)where $V = V_p - V_f$. As seen in Eq. (2), an exponential rise of the heat flux, Q, reaching the sample is expected when V is raised to V_p by strong SEE.

It must be noted here that Eqs. (1), (2) have a limited range of application, namely $\delta_e < 1$ [5] and do not take into account the space charge limited SEE current [6] and its effect on the floating potential of the surface [7]. Although there have been some attempts to derive analytical expressions for $\delta_e \geqslant 1$ values [6], [8], the conclusions of these models are still controversial. So, while a space charge-saturated value of the sheath voltage close to kTe was predicted by Takamura et al. [6] in the 1990s, the possibility of complete suppression of the sheath, and hence of the thermal isolation of the surface with respect to the plasma electrons, due to strong SEE has been very recently predicted [8].

Although the secondary electron emission of metals exposed to a plasma has been thoroughly addressed in relation to the interpretation and design of electrostatic probes [9] and Hall thrusters [10], among others, no direct measurement of this parameter, to our knowledge, for the main plasma facing materials of a fusion plasma has ever been reported. This is not the case for carbon, on which a modest increase, up to 20%, of the SEE coefficient was deduced in devoted experiments at the divertor injection tokamak experiment (DITE) in the early 1990s [11]. Interestingly, this effect was ascribed to surface effects due to hydrogen implantation [12]. In this work, the results for the case of He discharges shown in a previous publication [13] are extended to different plasma gas discharges (Ar and H_2) and other metals (W and SS) in order to study the observed Li SEE enhancement and to address the possible mechanisms related to it. The calculation of the SEE vs. electron mean energy has also been improved by the measurement of the electron energy distribution function (EEDF) of the studied glow discharges which is addressed in Ref. [14].

2. Experimental procedure

The experimental procedure has been described in the previous paper, together with some results [13]. Basically, a sample holder, on which the substrate is clamped or deposited (as in the case of Li films) is exposed to a low-density high plasma potential glow discharge plasma. The used dc-Glow discharges are produced in a SS chamber maintaining a positive voltage of around 300–500 V (depending on the desired parameters) between the anode and the chamber walls (cathode). The current vs. voltage characteristics, I/V, of the sample are recorded for bias values negative with respect to the plasma potential (ion saturation component). Working with low enough pressures and high plasma potential an anomaly in the I/V characteristics of the exposed materials is observed. In principle negative biasing of a surface with respect to the plasma potential will draw only an ion current to it, which increases up to the ion saturation current value. A measurement of this anomalous current can be obtained by subtracting the ion saturation current from the total current measured, thus obtaining the total electron current, I_e.

Fig. 1 shows the resulting I_e/V characteristics for the case of Li exposure at three different He plasma pressures. As it can be observed, for lower plasma pressures (and higher plasma potentials) the observed extra electron current increases. Clearly, this effect cannot be ascribed to ion-induced SEE as it increases for lower ion currents and energies. The effect is related to the presence of suprathermal electrons in this kind of glow discharges. In the presence of a high energy tail in the EEDF, commonly achieved at low neutral pressures of the order of $P < 1$ Pa and plasma currents of 100 mA $< I <$ 500 mA, the I/V curves show a large "dip" for voltage values close to the floating potential, deduced from the characteristics of a single Langmuir probe (W, diameter = 0.4 mm, length = 6 mm). This behavior is expected when a strong component of the electron current produced by SEE from the sample, adds to that from the ion current from the plasma [15]. By normalizing the extra electronic current to the flux of electrons impinging on the sample, I_{ei}, an effective SEE coefficient can be deduced. The I_{ei} can be calculated from the unidirectional (perpendicular to the sample) electron flux energy distribution function ($EEDF_1$), for the studied discharges, which is measured using a simple gridded probe as described in a previous paper [14]. For the case of He and Ar glow discharges the obtained $EEDF_1$ are well fitted to a bi-Maxwellian distribution which represents two fractions of the electron population: highly energetic electrons or "*hot*" electrons (suprathermal electrons) and electrons with lower energy or "*cold*" (bulk) electrons, expressed in the form:(3)where T_{hot} and T_{cold} correspond to the temperature (eV) of the *hot* electrons and *cold* electrons respectively and f_{hot} is the suprathermal electron fraction. Table 1 shows the fitted parameters for He and Ar.

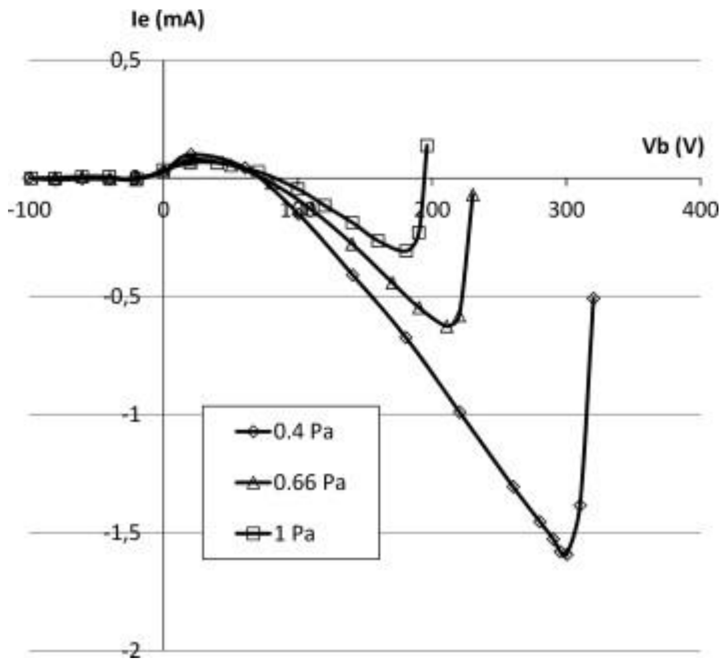

Fig. 1. I_e/V characteristics from the biasing of Li for He Dc-GD at three different pressures. Lines are drawn only for guidance.

Table 1. Bi-Maxwellian EEDF fitted parameters for the He and Ar Dc-GD plasmas.

Dc-GD plasma	f_{hot}	T_{hot} **(eV)**	T_{cold} **(eV)**
He	0.022	185	9
Ar	0.001	180	6

The mean energy at each bias voltage is then calculated from the $EEDF_1$ [14]. Taking into account the deceleration that electrons undergo in the sheath, the mean energy can be calculated as:(4)where v_1 is the electron velocity perpendicular to the target.

3. Results and discussion

3.1. SEE of Li, SS and W for He and Ar glow discharges

The results for the SEE vs. E_{mean} obtained in this manner for the case of He [13] and Ar glow discharge plasmas for Li as well as SS and W are shown in Fig. 2 (no values for E_{mean} < 40 eV are shown because the measurement and subtraction errors are no longer negligible for those values). The results for W and SS are not very different from the literature values [16], if allowance for the energy range of the present experiment is made. Thus, the maximum of the W SEE coefficient from the literature (1.35) takes place at an electron energy of 650 eV, whereas the maximum mean energy achieved in the present experiments is of about 120 eV, for which a lower value (0.95) is here reported. On the other hand, the difference from the literature value [10] for the case of the Li target is clearly visible. The maximum SEE yield calculated from the present experiments is at least five times larger than its bibliographic value (0, 5). The value of the maximum SEE from Fig. 2 is an underestimation of the value of the SEE vs. incident electron energy maximum due to the effect of the convolution used in Eq. (4).

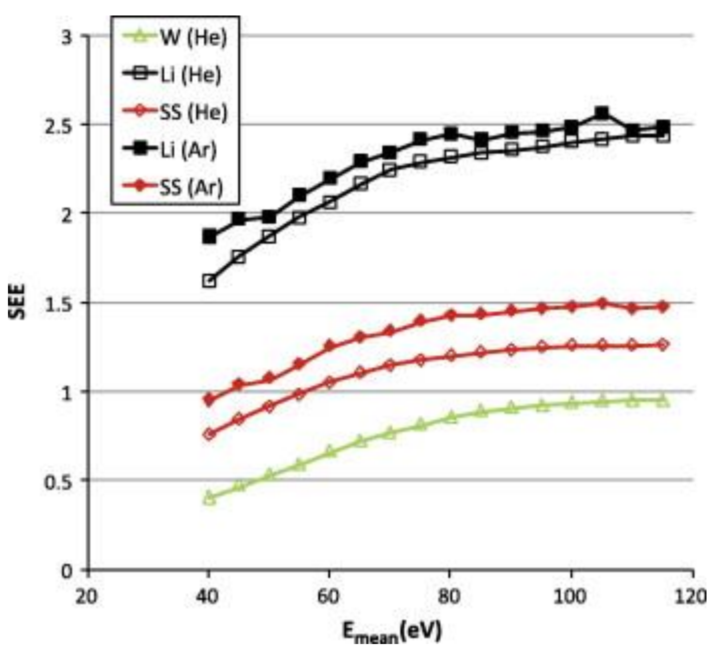

Fig. 2. Results of the Li, SS and W SEE yields vs. mean electron energy for He and Ar Dc-GD.

In order to analyze in more detail the difference of the obtained SEE with respect to theoretical values (no plasma immersed experiments) the ratio between the measured SEE at each bias, SEE_{exp} (V_b) and the SEE values obtained from the convolution of the theoretical *SEE* (E_i) [17] and the measured $EEDF_1$, SEE_{theo} (V_b), is obtained where,(5)Fig. 3 shows the obtained SEE_{exp}/SEE_{theo} ratios for SS, W and Li in He plasmas and SS and Li in Ar plasmas. Several conclusions can be extracted from these results. No major effect of the ion mass (i.e., Ar vs. He) or the the flux of incident suprathermal electrons is observed. Even though Ar plasmas have a 20 times lower suprathermal population than He plasmas the ratio does not change for Li or SS surfaces.

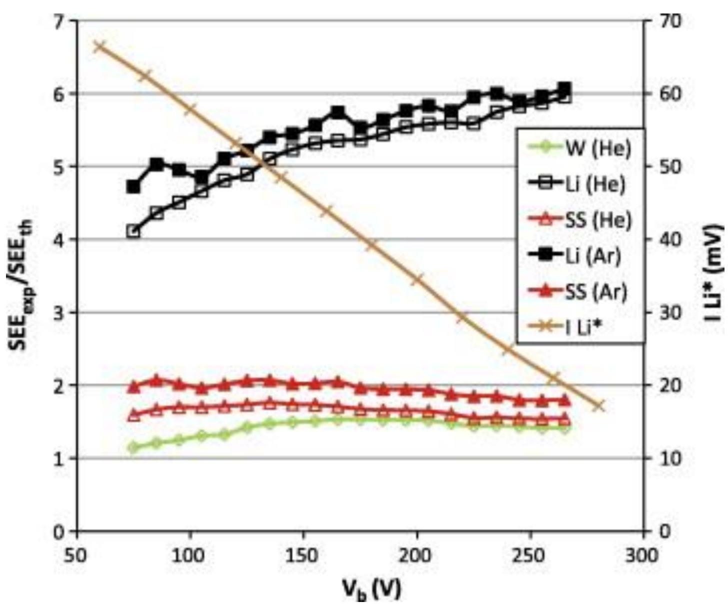

Fig. 3. SEE_{exp}/SEE_{theo} ratios for SS, W and Li in He plasmas and SS and Li in Ar plasmas.

The ratio increases as the bias is increased (lower sheath potential drop) for the case of Li, although it remains constant for W and SS. Fig. 3 also shows the value of the excited Li signal (using a LiI filter at 671 nm and a photomultiplier) as a measurement of the Li sputtered flux [18]. Contrary to what would be expected from a sputtering-induced enhancement of SEE, the SEE_{exp}/SEE_{theo} ratio increases as the sputtered flux decreases. Nevertheless, this increase can be also related to the increase in the mean energy of the incident electrons, which increases for higher V_b. Looking at the nature of both processes, ion sputtering by ion bombardment and electron emission by electron bombardment, it is clear that when both processes are working simultaneously on a material, they cannot be treated separately. The SEE yield is related to the electronic state of the surface, which may change when the material is simultaneously bombarded with ions, and even more when the material is sputtered mostly as positive ions, which is the case for Li. Conversely, the charge state of the sputtered material could be affected by the SEE process as well. Compared to other metals, alkali surfaces are prone to the ejection of ionic species during sputtering [19]. Two mechanisms for ion sputtering depending of ejection velocity have been put forward [20]. While charge exchange processed near the surface seems to dominate for high ion ejection velocities, the production of thermal spikes, leading to an effective electron temperature of a few eV in the solid, seems to account for the observed functionality at low ejection velocities. Since a higher electron temperature would lead to an easier detachment of the electrons at the conduction band (thermo-ionic emission), it can be postulated that the enhancement of the local electron temperature upon sputtering can be behind the observed phenomena. Interestingly, the fraction of sputtered Li as ions has been found to be independent of the bombarding ion mass [21], which is in line with the observed results for Li enhanced SEE, pointing to a possible common mechanism of these two phenomena.

3.2. SEE of Li and SS for H_2 glow discharge

In order to extend these results to a more relevant fusion-related scenario, the same experiments were performed in Hydrogen plasmas for SS and Li. Unfortunately, for the case of hydrogen, the measurement of the EEDF for the same conditions as the *I*/*V* curves measurements was not possible due to the effect of hydrogen absorption of the walls, which changes the plasma conditions over time, thus no measurement of the SEE vs. mean energy was possible. Nevertheless, from direct comparison of the *I*/*V* curves for SS and Li cases in a hydrogen Dc-GD plasma (see Fig. 4), two clear statements can be made. Both materials present a SEE yield higher than one (a net electron current leaving the sample is seen for $V_b > 50$–100 eV) and the SEE yield of Li is significantly higher than that of SS.

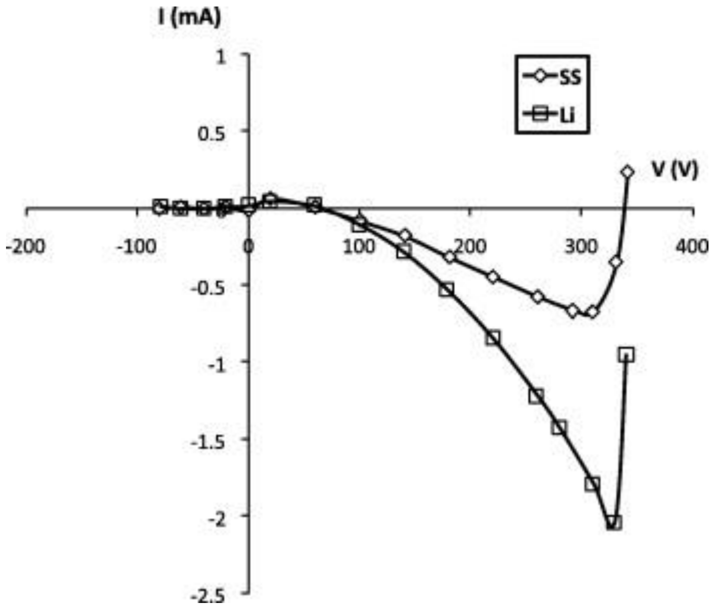

Fig. 4. *I*/*V* characteristics from the biasing of the Li and SS targets for H_2 Dc-GD. Lines are drawn only for guidance.

3.3. Effect of surface oxidation in Li SEE

Since the SEE yield of materials is very sensitive to the surface chemical state and Li is known as a strong oxygen getter, one of the possible reasons for the strongly enhanced SEE yield of Li surfaces could be surface oxidation [22]. This could be produced by the residual water and air leaks in the reactor. Therefore, the effect of oxygen addition in the sputtering and the SEE yields of Li surfaces was intentionally addressed [13]. A concomitant decrease of the SEE and sputtering yields were observed upon increasing the surface concentration of O with respect to pure Li, thus eliminating the possibility of oxygen enhanced SEE.

3.4. Implications of enhanced SEE emission of Li surfaces

Finally, it is important to briefly address the implications of the enhanced SEE emission of Li surfaces under a fusion plasma scenario. Although the fact that Li coatings in a fusion device lead to a clear enhancement of plasma confinement characteristics is broadly accepted at present, the extraordinary low recycling properties of Li exposed to a hydrogen plasma have been put forward as the underlying driver [23]. However, the results here reported may point to another, perhaps complementary, player. For the typical high electron temperatures obtained under Li operation at the edge region, the injection of electrons deduced from the SEE yields displayed in Fig. 2 could produce a strong distortion of the plasma sheath. In that sense, the effect of Li exposure would be very much equivalent to external biasing of the PFC's, a well known technique for the development of enhanced confinement modes in Tokamaks [24]. A previous work [25] also showed that an increased secondary emission from the limiters results in a reduction of the electron and ion temperatures in the scrapeoff and a rise near the center in addition to a neutral density drop throughout the device due to the reduced sheath potential. Care must be taken however when extrapolating the present findings to present fusion plasma since, being a surface specific phenomena, the impact of surface contaminants such as carbon and oxygen, commonly found as the main plasma impurity, must be accounted for. Among the concomitant unwanted effects to be expected, the suppression of the sheath by high δ_e would lead to a strong enhancement of the electronic heat loads to the plasma exposed material. Research in these topics is being performed in TJ-II at present.

4. Conclusions

In conclusion, experimental evidence of the strong enhancement of the SEE coefficient of fresh Li surfaces by exposure to Dc-GD plasmas at low pressure is here reported. In contrast, only a slight enhancement of the SEE for SS and W samples was seen. The study of SEE on different plasma gas discharges (He, Ar and H_2) show no major dependence on the bombarding ion mass or the incident electron flux for the case of Li and SS surfaces. This new phenomenon could be playing a significant role in the reported enhanced performance of fusion plasmas under Li surroundings and have an important impact for all applications where high SEE is relevant.

Acknowledgements

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References

[1] S.I. Itoh, K. Itoh, Phys. Rev. Lett. 60 (1988) 2276.

[2] A.R. Kraus, D.M. Gruen, J. Nucl. Mater. 85 & 86 (1979) 1179.
[3] P.C. Stangeby, in: P. Stott, H. Wilhelmssonin (Eds.), The Plasma Boundary of Magnetic Fusion Devices, Nicki Dennis, Philadelphia, 2000.
[4] N. Hershkovitz, IEEE Trans. Plasma Sci. 22 (1994) 11.
[5] M.D. Campanell, A.V. Khrabrov, I.D. Kaganovich, Phys. Rev. Lett. 108 (2012) 235001.
[6] S. Takamura et al., Phys. Plasmas 5 (1998) 2151.
[7] M.Y. Ye, S. Takamura, Phys. Plasmas 7 (2000) 3457.
[8] M.D. Campanell, A.V. Khravrov, I.D. Kaganovich, Phys. Rev. Lett. 108 (2012) 255001.
[9] G. Fuchs et al., J. Nucl. Mater. 145–147 (1987) 268.
[10] D. Sydorenko, I. Kaganovich, Y. Raitses, A. Smolyakov, Phys. Rev. Lett. 103 (2009) 14.
[11] R.A. Pitts, G.F. Matthews, J. Nucl. Mater. 176 & 177 (1990) 877.
[12] M.E. Woodst et al., J. Phys. D: Appl. Phys. 20 (1987) 1136.
[13] E. Oyarzabal et al., J. Nucl. Mater. 438 (2013) S792–S795, http://dx.doi.org/10.1016/j.jnucmat.2013.01.170.
[14] A.B. Martin-Rojo, E. Oyarzabal, F.L. Tabarés, Plasma Sources Sci. Technol. 22 (2013) 035001.
[15] M.C. Griskey, R.L. Stenzel, Phys. Rev. Lett. 82 (3) (1999) 556.
[16] D.N. Ruzic, R. Moore, D. Manos, S. Cohen, J. Vac. Sci. Technol. 20 (1982) 1313–1316.
[17] R. Kollath, Handbuch Der Physik 21, Springer-Verlag, Berlin, 1956.
[18] F.L. Tabarés et al., Fusion Eng. Des. 87 (2012) 1741–1746.
[19] J.P. Allain, J.N. Brooks, D.A. Alman, L.E. Gonzalez, J. Nucl. Mater. 337–339 (2005) 94–98.
[20] B. Weidtmann, A. Duvenbeck, A. Wucher, Appl. Surf. Sci. 255 (2008) 813–815.
[21] J.P. Allain, D.N. Ruzic, Nucl. Fusion 42 (2002) 202–210.
[22] H. Bruining, J.H. de Boer, In Part 1 of Secondary electron emission, (N. V. Philips' Gloeilampenfabrieken, 1938), 1938.
[23] R. Maingi et al., Phys. Rev. Lett. 107 (2011) 145004.
[24] R.R. Weynants, G. van Oost, Plasma Phys. Control Fusion 35 (1993) B177.
[25] J. Mandrekas, C.E. Singer, D.N. Ruzic, J. Vac. Sci. Technol. A 5 (1987) 2315–2318.