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Impurity release and recycling behaviour in TEXTOR-94 with siliconised walls

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Abstract

Siliconisation has been performed for a long period of operation as the routine wall coating procedure of TEXTOR-94. The general aim was to study the behaviour of TEXTOR-94 with a medium-*Z* plasma-facing material and to compare it with that under freshly boronised as well as 'carbon dominated' conditions. This contribution focuses on the characteristics of Si-impurity release from the limiters, and the influence of the Si coating on the release of carbon and oxygen impurities with special emphasis on material mixing effects on the plasma-exposed surfaces. © 2001 Published by Elsevier Science B.V.

Keywords: Siliconization; Sputtering; Chemical erosion; TEXTOR

1. Introduction

Wall coatings provide an easy tool for studying plasma behaviour under different wall conditions. The benefit of carbonisation [1] and the use of graphite on a large scale was the elimination of the medium-*Z* metal impurities which, in connection with large amounts oxygen impurities, radiated energy from the plasma core and hindered the achievement of high-performance plasmas. With carbon-dominated wall surfaces the impurity radiation shifted from the core to the edge of the plasma. Further progress was achieved by boronisation, which reduced the oxygen level significantly, increased thereby the density limit and eased the density control by improved dynamic wall pumping [2].

Wall coating with silicon in TEXTOR was first explored in 1992 [3,4]. Operation with siliconised walls highlighted in particular the complex relation between the wall material properties, the impurity radiation behaviour, the plasma edge and general plasma properties. In this sense, the use of silicon was embedded in the program of a concept for a 'radiative boundary' [5], which aims to spread the power on large areas by edge impurity radiation. The establishment of high edge radiation levels led also to an operation mode with increased energy confinement (RI-mode) [6], which is accessed routinely in TEXTOR-94 using inert impurity seeding (neon). But coating of the walls with silicon allows also the achievement of this regime with silicon as the main radiator and with (physical) Si sputtering as the dominant intrinsic impurity source [3]. During the last two years siliconisation has been applied regularly in TEXTOR-94 to investigate this behaviour in greater detail and to compare the behaviour with the extended database for RI-mode operation behaviour with boronised walls and radiation by neon impurity seeding. Improved wall and limiter diagnostics have been installed in TEXTOR, mainly concentrating on limiter lock systems, which allow a detailed investigation of local impurity release characteristics and material mixing effects.

This contribution focuses on the analysis of the Si-impurity release characteristics from limiters and the analysis of the behaviour of carbon and oxygen as the remaining impurities of importance. In addition the

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effects of mixing of freshly Si-coated graphite surfaces with carbon and deposition of Si on non-coated graphite surfaces are described. The influence of the siliconisation on operational limits is described elsewhere [7].

2. Experimental

TEXTOR-94 has been siliconised using the standard RF assisted DC plasma in a mixture of 80% He and 20% SiH_4 or SiD_4 as precursor gas at a wall temperature of 300°C or 350°C, a total current of 8 A and a DC voltage of typically 600 V. Probes were positioned routinely at three different locations inside the torus and their post mortem analysis showed pure Si films with a thickness of 120–150 nm, demonstrating that the Si film is deposited rather uniformly over the entire wall. The properties of the Si films are described elsewhere [8]. The impurity release behaviour was measured by emission spectroscopy on the toroidal ALT pump limiter and in addition on two graphite test limiters introduced through limiter locks from the bottom and the top of the machine. The C, O and Si impurity release yields have been determined from CI (909 nm) and OI (844 nm) lines and from an SiII line at 597.9 nm using interference filters and S/XB ratios taken from literature values. In addition a spectrometer operating in the wavelength range from 400 to 440 nm observing BII (412 nm), SiII (412.5 nm), CII (426.7 nm), H_γ (434 nm) and the CD band emission at 432 nm was employed. Yields have been evaluated using (S/XB (CII)):(S/XB (D_γ)) = 0.035, (S/XB (OII)):(S/XB (Dγ)) = 0.1 and (S/XB (SiII)):(S/XB (D_γ)) = 0.05. SiH_4 injection through a hole in a graphite test limiter has been used to calibrate the SiD molecular emission versus SiII radiation. Plasma edge parameters have been measured by He- and Li-atomic beam techniques.

For the results reported here, TEXTOR-94 was operated under standard conditions of 350 kA, 2.25 T and 1.3 MW NBI co-injection. Slow density ramps were performed to study the density dependence of the impurity release characteristics.

3. Results and discussion

3.1. Impurity release

Under freshly siliconised conditions, silicon is the dominant species released from the limiters and in the plasma. Due to a gradual and steady increase of the carbon impurities in the plasma this condition last only for less than about 20 discharges. We will address at first the observations which are obtained under fresh siliconised conditions representing a 'full silicon wall surrounding' and describe the temporal behaviour in the following section.

Fig. 1 shows the density dependence of the impurity flux ratios measured at a graphite test limiter coated during the siliconisation. At lower plasma densities the effective silicon yields reach values of up to 20% and decrease down to about 2% at the highest plasma densities. For deuterium impact on silicon, physical sputter yields are between 1.5% and 2.5% for the relevant range of plasma edge temperatures of 30–80 eV and thus similar to those for graphite. The high yields at low densities result from Si self-sputtering, which is about 0.75 at $T_e = 50$ eV and approaches unity at $T_e = 100$ eV for four-times-ionised Si ions impinging on Si. At these densities the radiation level is also close to unity leading to strong cooling of the plasma edge and a highly non-linear coupling develops between the steeply increasing Si release by self-sputtering and cooling by increasing radiation losses from Si. Obviously, the system stabilises and a so-called 'self-sputtering catastrophe' does not develop. At the plasma edge, however, hydrogen is largely diluted, which results in an apparent increase of the oxygen and carbon release yields when related to the hydrogen flux as seen in Fig. 1. Under these conditions carbon is released predominantly by sputtering through Si impact. The solid lines in the figure show the modelled Si and C release based on the measured hydrogen, carbon, oxygen and Si fluxes, the edge electron and ion temperature (which is about twice the electron temperature at low plasma densities). Physical sputtering at normal incidence has been assumed and a C/Si ratio of 0.3 at the top surface layer of the limiter. The agreement is quite good at lower plasma densities with some deviations at higher densities in D plasmas, which are not clarified yet. The oxygen yield cannot be modelled easily as the oxygen sources are not fully clarified. However, it seems likely that a significant contribution

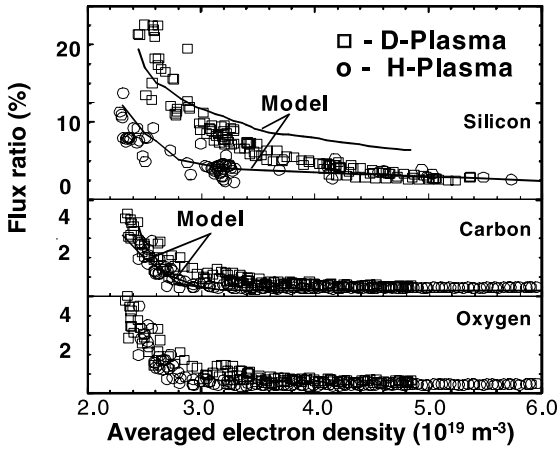

Fig. 1. Effective release yields of silicon, carbon and oxygen as functions of plasma density. Fresh siliconised conditions.

to release of oxygen from the entire wall is due to VUV photons. The possible chemical release of Si has been analysed by emission spectroscopy of the SiD molecular band at 414 nm and by residual gas analysis after the discharges. The upper part of Fig. 2 shows the evolution of the Si^+ and SiD band light during the injection of a calibrated SiH_4 flux through a hole in a graphite test limiter and the lower part the emission spectrum during normal plasma surface interaction under freshly siliconised conditions. Fig. 3 shows a residual gas spectrum taken during the maximum of the pressure rise after the end of a discharge. The appearance of SiD_4 should appear on masses 32 and 34. None of these measurements indicates a significant contribution of chemically released Si. An upper limit of 0.03% for the contribution of SiD_4 to the Si release yield can be estimated. This is also confirmed by the SiD spectroscopy.

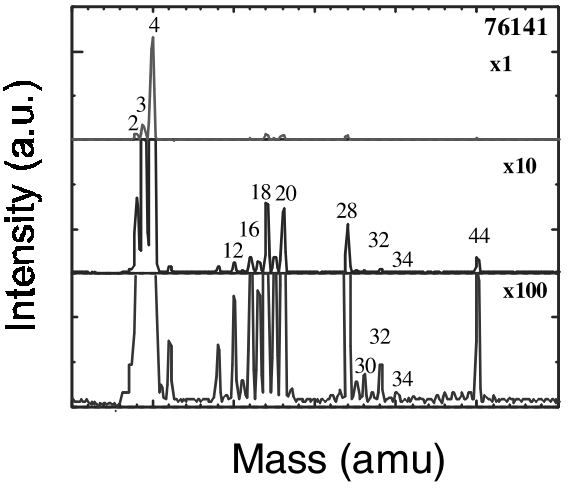

Fig. 3. Residual gas spectrum taken after the end of a discharge when the neutral gas pressure is about at the maximum. The figure shows the spectrum in three different amplifications. SiD_4 should appear at masses 32 and 34, which are below 10^{-2} of the hydrogen pressure and can be largely explained by the formation of deuterated hydrocarbons.

3.2. Temporal behaviour and material mixing effects

Fig. 4 shows the development of carbon, oxygen and Si fluxes measured at the ALT main limiter after a

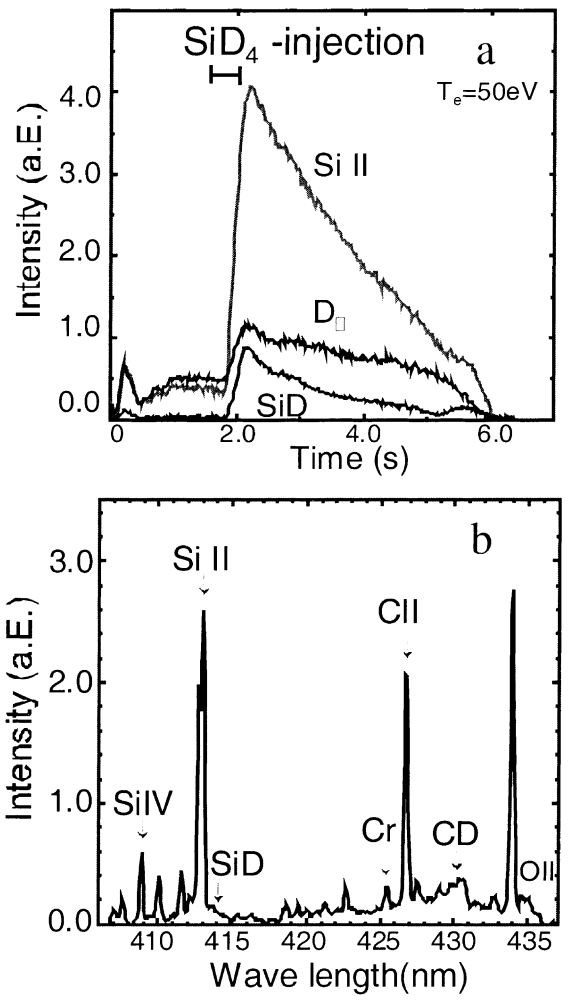

Fig. 2. (a) Evolution of the SiII, D_γ and SiD molecular light during the injection of SiH_4 through a hole in a graphite test limiter; (b) emission spectrum in front of a siliconised graphite test limiter.

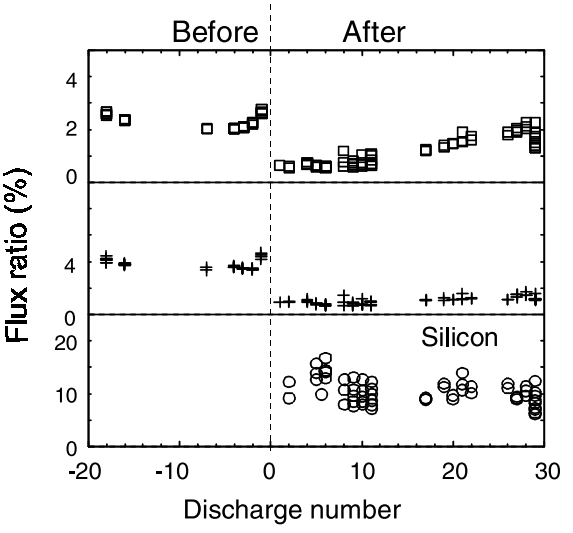

Fig. 4. Evolution of the relative flux ratios of carbon, oxygen and silicon measured on the ALT toroidal limiter as a function of shot number. The data are for a density of $3 \times 10^{13}/cm^3$ with 1.3 MW co-injection.

siliconisation in SiD_4 as function of the shot number. The data are for 1.3 MW D co-injection heating at $n_e = 3 \times 10^{19}/m^3$. The siliconisation reduces the carbon and oxygen fluxes to values below 0.5%. The Si release dominates with yields of about 10% at this low plasma density. This behaviour is also observed on SiXII VUV impurity emission lines taken for the same shots. Interestingly, the carbon fluxes and the CIII radiation increase steadily until after about 30 discharges they reach the same level as before, whereas the oxygen and silicon fluxes and SiXII radiation does not change much during this shot sequence. The increase of the carbon results from a continuously progressing mixing of the Si surfaces with carbon that is released from highly loaded edges at the limiters from which the Si is eroded quickly and also partly from C released from remote molecular carbon sources (CO, C_xH_x, ...). The increasing carbon flux leads also to additional sputtering of Si from the Si/C mixed surfaces which compensates the reduction of the Si release due to a decreasing Si concentration in the surfaces due to the mixing with C.

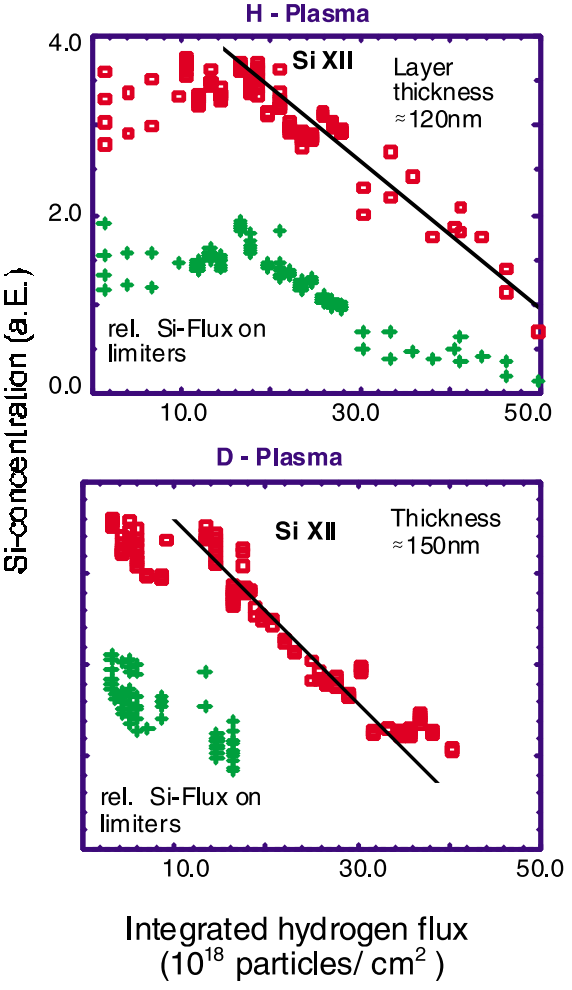

Fig. 5. Evolution of the SiXII light emission and the Si flux ratio on the limiters as a function of the integrated flux on the limiter of hydrogen and deuterium plasma conditions.

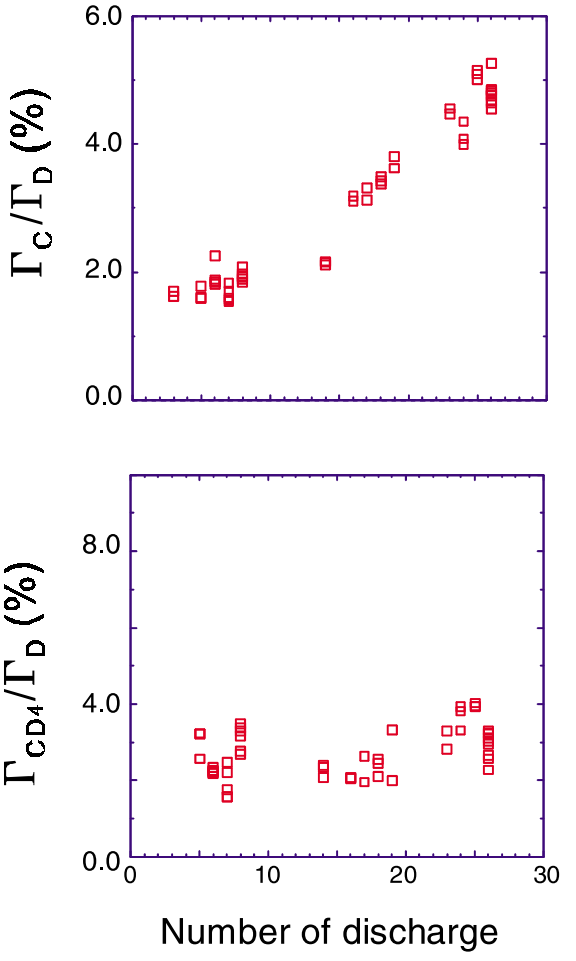

Fig. 6. Development of the C^+ and CD flux ratio as function of the discharge number for a graphite test limiter inserted in a freshly siliconised TEXTOR environment.

Fig. 5 shows the behaviour of the Si XII radiation and the Si fluxes on the ALT limiter on a longer time scale for identical plasma conditions. The Si level is rather stable up to an fluence of about $2 \times 10^{19}/cm^2$ s from which on the Si concentration and the Si fluxes steadily decrease. This flux is about four times more than the flux which is estimated to erode the Si layer of 150 nm. This indicates that about 80% of the eroded Si return to the limiter prolonging the lifetime of the Si coating. The remaining smaller part (≈20%) of the Si diffuses into deeper regions of the SOL and is lost by deposition on side walls of limiters or other obstacles in the SOL. The shorter SiXII decay time observed in D

discharges is due to larger physical sputtering by deuterium impact.

Fig. 6 shows the temporal behaviour of the C^+ and CD radiation in front of a graphite limiter inserted in a freshly siliconised TEXTOR-94 surrounding. As can be seen, the C^+ light starts at a low level but increases then steadily up to values similar to the one without siliconisation whereas the CD band emission is about constant during this period and similar to pure graphite limiters. This can be understood taking into account the fact that carbon atoms released by physical sputtering originate from the first two monolayers and the deposition of Si from the background plasma decreases the C concentration in this top layer. The increasing C^+ signal reflects the increase of the C fraction in the incoming flux. The Si deposition does not influence much the CD emission, indicating that the CD_4 formation occurs in deeper layers inside the C surface not much influenced by the Si layer on top of the graphite. Obviously the C^+ signal just at the beginning of this shot sequence results exclusively from the break-up of CD_4 and the increase of the C^+ signal from increasing physical sputtering of C from the top surface layer.

4. Summary

After siliconisation, silicon is the main plasma impurity for about 30 auxiliary heated discharges (1.3 MW). The oxygen impurity content is reduced significantly and remains low for longer periods. The carbon impurity content recovers continuously within about 30 shots: this results from the deposition of carbon on the Si surfaces produced at localised areas at which the Si layer is eroded quickly and also from molecular carbon sources at remote areas. The Si is released by physical sputtering with a strong contribution of Si self-sputtering at low plasma densities. Several observations show that a possible significant contribution from chemical SiD_4 formation to the overall Si release can be ruled out. Deposition of Si from background Si fluxes on pure graphite surfaces reduces the physical sputtering of C due to the covering of the top surface with Si but leaves the CD_4 formation nearly unaffected, showing that hydrocarbon molecules are formed in deeper layers of the graphite surface. The lifetime of the coating is about five times longer as estimated from gross erosion indicating that about 80% of the eroded Si return to the location of production. The remaining part of Si is deposited on areas in the SOL and is responsible for the limited lifetime of the coating.

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