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IMPURITY CONTROL OF TOKAMAKS WITH IN SITU METAL DEPOSITION*

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Metal coatings of titanium and chromium of different thickness were deposited in situ in microtor and macrotor tokamaks and tested for impurity control. To improve the microstructure of the metal deposit, Ti and Cr were evaporated at a slow rate of about 20 Å/h during discharge cleaning. A 200 Å fresh metal deposition is required to obtain oxygen free surface layers. The oxygen control by Cr deposits was comparable to the one with Ti coatings. The hydrogen recycling rate increased markedly for Cr deposits. Control measurements show that the problem of hydrogen and deuterium retention in the metal coating during a switchover from one gas to the other can be overcome by short time outgassing to 650 K.

1. Introduction

A high desorption rate of the low-Z impurities, oxygen and carbon, from the surfaces and the retention of hydrogen adversely influence almost every aspect of plasma behavior in a research tokamak. Various methods of discharge cleaning and titanium gettering are now widely used to reduce the oxygen and carbon contamination of the plasma. At the higher plasma temperatures achieved by supplemental heating the influx of high-Z metal impurities remains a critical problem. Here we wish to report on a study of in situ surface deposition of metal coatings. The purpose of the study was to reduce the oxygen contamination, to develop a quick procedure for impurity control after venting the machine to air, and possibly to reduce the metal influx by improving the microstructure of the metal lattice.

2. Titanium and chromium deposition during discharge cleaning

Though a tremendous reduction of loosely absorbed oxygen and carbon impurities was achieved by discharge cleaning only, it was realized that removal of the impurities from near-surface layers could be achieved only by long time discharge cleaning or baking of the chamber. To avoid this time-consuming procedure one can use in situ deposition of metals. These experiments were aimed at going beyond the gettering action previously employed in tokamaks.

It was found that a clean surface layer of about 0.1 μm is needed to accommodate the absorption and diffusion of hydrogen into a metal lattice without release of other gaseous atoms already there. Such clean surface layers have been readily produced by vapor deposition of Ti and Cr.

Though titanium gettering is widely used to reduce impurity levels in tokamaks [1–4] not much attention has been given to the fact that the microstructure and properties of deposited titanium depend to a large extent on deposition technology and substrate temperature. Evaporated atoms arriving on the surface are often stuck at a position where they are somewhat loosely bound [5]. Depending on the effective binding energy thermal motion can cause desorption or migration of the atom on the surface to sites where they are more tightly bound. Consequently, the microstructure of a coating depends on the surface mobility of ada-

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toms which is primarily determined by the temperature of the substrate and the kinetic energy of the incoming atoms.

Three differently structured titanium coatings with different physical and chemical impurities are found in the deposition process of pure titanium as a function of the substrate temperature [6]. At room temperature surface mobility is limited and imperfections in the growing titanium crystal lattice are abundant and randomly distributed. As a result, the titanium coating grows in the form of tapered crystallites or cones with pores in between with dimensions of a few hundred ångströms. This large area structure of the titanium film probably enhances the titanium influx during plasma surface contact as well as the diffusion of hydrogen into the metal. The number of micropores and imperfections decreases markedly at higher substrate temperature.

To improve the microstructure of the metal deposit, Ti and Cr were evaporated at a very slow rate of about 20 Å/h during discharge cleaning. Under these conditions the periodic bombardment of the surface by H^+ and Ti^+ ions leads to local surface heating at the point of impact and energy release due to recombination. Conductive heat transfer to neighboring atoms and atomic layers in the substrate leads to very rapid cooling. Loosely bound adatoms are either desorbed and go back into the plasma or migrate over one or a few atomic distances until they fall into a potential well where they are most tightly bound to the crystal structure.

In the following sections we will describe the experimental procedures and results relating to the in situ plasma deposition of the metal coatings (Ti and Cr), used for the last year in microtor/macrotor tokamaks under the demanding conditions of RF heating (up to 0.5 MW in macrotor) and high density (up to $5 \times 10^{14}/cm^3$ in microtor).

The objectives of the recent experiments were: (1) to develop a quick method of impurity control for present day devices; (2) to reduce the metallic influx during RF heating; and (3) to study the properties of "good" surfaces.

3. Plasma devices and parameters

Macrotor has a 20 m^2 surface area and two deposition stations of the sublimation type. These stations can cover nearly all inside surfaces seen in the absence of plasma-gas scattering due to the low aspect ratio. The other parameters of macrotor have been described elsewhere [7]. Microtor is a high current density tokamak operated at 25 kG, 120 kA, and $5 \times 10^{14}/cm^3$ without a poloidal limiter.

Ti and Cr coatings were deposited under identical conditions during discharge cleaning. Both Ti and Cr sublimate readily. The deposition thickness was monitored by quartz crystal monitors sensitive to one monolayer. The minimum thickness deposited was greater than 200 monolayers. Ti coating applied during discharge cleaning has been used successfully in macrotor as a fast impurity control method when regular daily venting was required during rf antenna studies which were carried out for weeks at a time.

4. Results

4.1. Oxygen control

Equally good control of oxygen and carbon impurity levels, $n_{ox}/n_H < 10^{-3}$, has been achieved with Ti and Cr coatings under normal macrotor discharge conditions. However, depending on the thickness of the coating, more or less oxygen appears later during the discharge when the hydrogen dose to the wall increases. For a too thin coating significant oxygen influx has also been observed at higher plasma and energy densities even when the surfaces are initially clean. In this case no oxygen is seen in the current initiation phase. By depositing different amounts of Ti, we have determined that oxygen will be present in disturbing amounts if the surfaces are not shielded with 50 Å deep fresh Ti coating.

Fig. 1 shows the experimental observations. Trace A is for discharges with surface oxygen contamination present. "Clean" surfaces on which oxygen has been gettered out such that the initial oxygen concentration is $\leq 3 \times 10^9\ cm^{-3}$

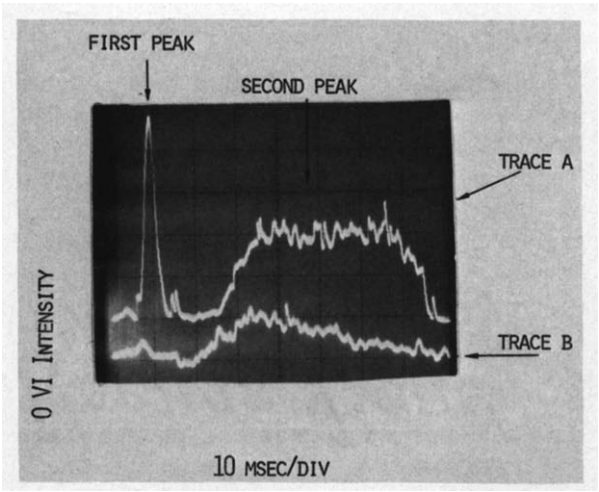

Fig. 1. Oxygen influx for surface contaminated systems (trace A) and for conditions when the surface is clean but the near surface is not (trace B).

show trace A type behavior with large oxygen influx observable in the current initiation phase. Trace B shows the oxygen influx for surfaces where fresh Ti has been deposited. Trace B clearly shows that the surface oxygen is missing when more Ti is deposited than is required to reduce the partial oxygen pressure by gettering.

Even with a freshly deposited Ti coating, we found it difficult to reduce the late time "bulk peak" shown in trace B. The metal deposition required to obtain surface layers free of oxygen depends on the initial contamination. After a large exposure to air, discharge cleaning and a thermal evaporation of about 500 Å are required to obtain a clean tokamak plasma. A small exposure to air requires about 100 Å thick layer deposited during discharge cleaning. Routine day-to-day operations requires a slow deposition of about 50 Å per day during discharge cleaning.

4.2. *ICRF heating induced desorption*

The above difficulties of impurity release from Ti coated walls manifest themselves even more when ICRF heating is applied. Fig. 2A shows the oxygen increase during the rf pulse. Fig. 2B shows the desorption of He in a hydrogen plasma after operating in He gas. This influx of

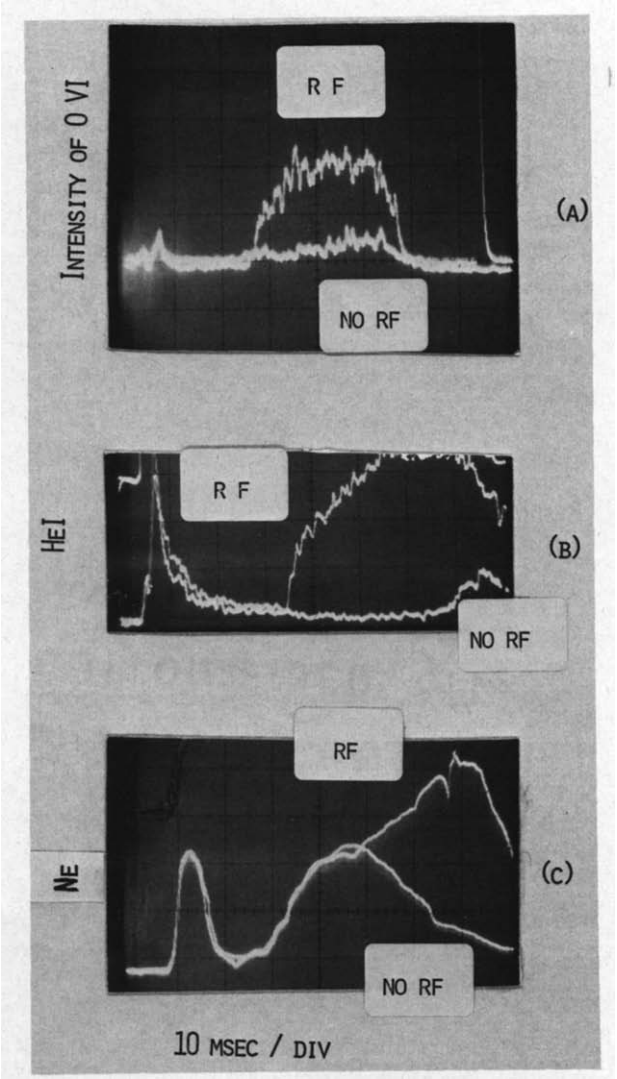

Fig. 2. RF induced desorption of oxygen and helium. The increase of influx is attributed to an increase in proton bombardment energy.

He was large enough to actually increase the plasma density, shown in fig. 2C, where the density normally would fall if no such influx were induced. These results are again evidence of the general rule that at higher plasma energies an increased impurity influx occurs. Similar results were obtained by enhanced ion bombardment of the wall caused by biasing the plasma positive with respect to the wall. The bias is accomplished

by removing electrons from the plasma, as described previously [8].

4.3. Hydrogen recycling

Ti and Cr coated walls were compared for the rate of hydrogen recycling. The recycling was evaluated from the rate of the density drop following discharge initiation but prior to the commencement of gas puffing (see fig. 3). After discharge initiation the density fell about six times more rapidly with the Ti coated wall, as was expected.

4.4. D–H exchange and retention

The D–H exchange has become a major unsolved problem in macrotor owing to the nature of the Ti deposition scheme, aided by continuous discharge cleaning in H_2. The walls are always completely saturated with hydrogen. Most of this is in the form of TiH_2 [9]. When deuterium experiments are required, the usual switchover to deuterium plasmas is never better than 95% complete. To achieve even this concentration will require weeks of discharge cleaning in D_2 combined with Ti deposition.

Cr and Cu depositions were tried to reduce the switchover time. However, no practical time-saving was realized. Even helium, which can only be present interstitially, exhibits a switchover problem, as was shown in fig. 2b. We are considering how to out-gas the walls by baking for a better control of the D/H ratio.

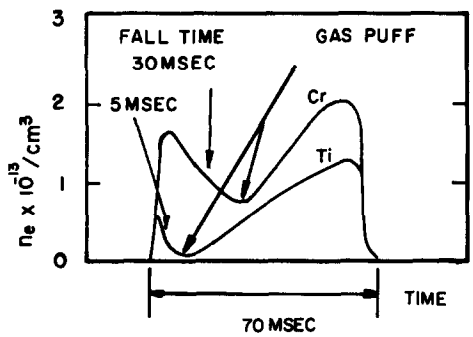

Fig. 3. Electron density behavior with Ti and Cr coated walls. The density fall time after ionization is an indication of recycling.

4.5. Thermal ramp outgassing of H and D

Samples of Ti coated antenna shields of macrotor which were exposed to H and D during rf heating experiments were thermally outgassed in Microtor's vacuum system. The mass analyzer was used to measure the release of H and D as a function of time and temperature. The time dependence of H and D release from the sample was identical. The outgassing peaked near 650 K for temperature ramping rates of 10°/s, in agreement with previously known results [10].

Fig. 4 shows the result of a typical run. Fig. 5 shows the Auger depth profile analysis of the samples before outgassing. No information has been obtained about the oxygen from our outgassing experiments. The Auger profiles represent a one-year history of macrotor. It is clear to us that no vital information can, at the moment, be extracted about the day-to-day purity of a tokamak from this type of analysis. This is not in contradiction with the previous experience of one of the authors (R.J.T.), with

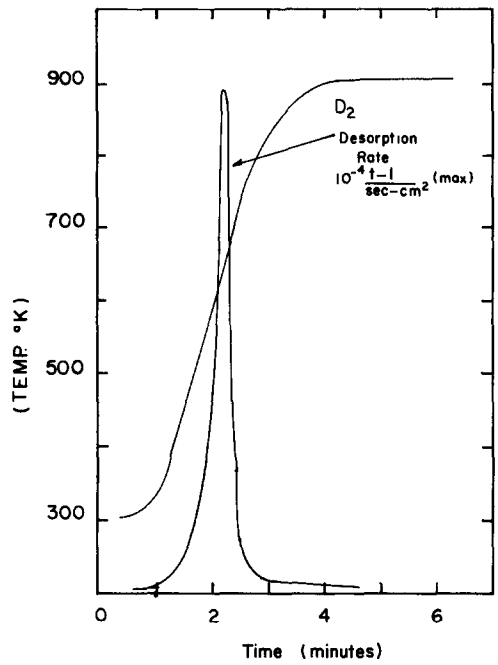

Fig. 4. Standard thermal ramp desorption of D and H from macrotor antenna samples. The maximum rate of desorption occurs at 650 K.

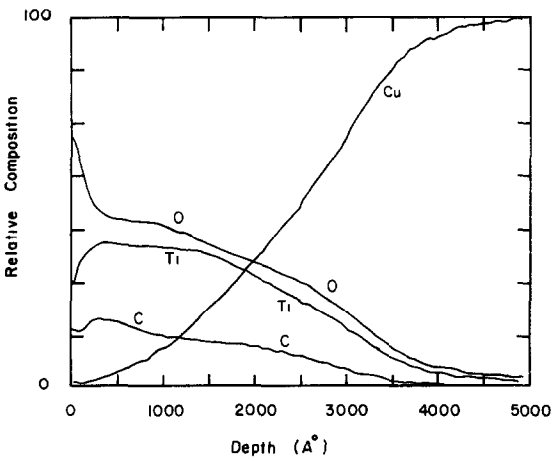

Fig. 5. Auger scan of the type of samples used for fig. 4. No correlation to machine impurity condition can be established from these data.

the results and significance of these analyses to date. This difficulty must be resolved by extended in situ analysis of surfaces on the in-between-shots basis.

5. Conclusions

Clean tokamak operation has been achieved by coating the walls with Ti and Cr at a slow rate during discharge cleaning. Differentiation has been made between impurity influx from surfaces and near-surface layers, 50–100 Å deep. Neither Ti nor Cr coatings applied 200 Å thick have provided for a rapid control of the D/H switchover problem. The control of the D/H ratio requires heating and outgassing of the coating. The deposition technique plays a vital role in structuring the coating and in the amount of metal influx. More quantitative experiments are needed on this subject. For the next generation of tokamaks the control of the surface composition and surface microstructure to 1000 Å and beyond will be essential for impurity control.

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