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ICRF siliconization in HT-7 superconducting tokamak

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Abstract

A new wall-conditioning method, ICRF plasma-assisted coating with silicon film, the so-called RF-siliconization, has been developed in HT-7 superconducting tokamak. It leads to suppression of carbon and oxygen impurities effectively. The properties of deposits were investigated by X-ray photoelectron spectroscopy (XPS). Silicon atoms have a large sticking probability on the wall and are practically less recycling. Plasma performance has been improved after ICRF siliconization. © 2001 Published by Elsevier Science B.V.

Keywords: Siliconization

1. Introduction

For tokamak experiments, one of the key points is how to control impurity level, reducing hydrogen recycling and achieve the better plasma. Plasma impurities cause two important effects: parasitic radiating power and dilution of fuel particles. For getting good wall condition, many standard wall-conditioning techniques, such as baking, glow discharge cleaning (GDC), taylor discharge cleaning (TDC) and boronization, have been applied in HT-7 superconducting tokamak. These techniques have been demonstrated to be very effective to reduce H_2O, C and O contents and achieving good discharges. Impurity control is one of the most crucial requirements for future fusion reactor. Recently, a better wall-conditioning method, ICRF plasma-assisted coating of thin silicon film, so-called ICRF-siliconization, has been used in HT-7 superconducting tokamak, to enhance the gettering efficiency of oxygen impurity and simultaneously establish a radiative plasma boundary.

Siliconization was first applied in the TEXTOR tokamak, where silane (SiH_4) diluted by more than 90% of helium was used. Compared to the boronized walls, tokamak discharges after the siliconization are characterized by a further reduction of low-Z impurities in the plasma (B, C, and O). The radiation due to Si is located at the plasma periphery. In presence of strong radiative edge cooling, the density limits, associated often with occurrence of MARFES, are enhanced by ~30%. Improved energy confinement under high power heating conditions was achieved at high line averaged densities. No indication for impurity accumulation was observed in these regimes [1–5].

2. Experimental setup and siliconization

The main parameters of HT-7 superconducting tokamak are $I_p = 100$–200 kA, $B_t = 1.5$–2.5 T, $a = 27$–28.5 cm, $R = 122$ cm, line-averaged density $n_e = 1$–5×10^{19} m^{-3}, $T_e = 1.0$ keV, and $T_i = 0.5$ keV, with a molybdenum limiter configuration. A stainless-steel liner is installed in the vacuum chamber with a radius of 32 cm. A new siliconization system has been installed in HT-7 superconducting tokamak as shown in Fig. 1. It consists of the following parts: (1) A stainless steel container for

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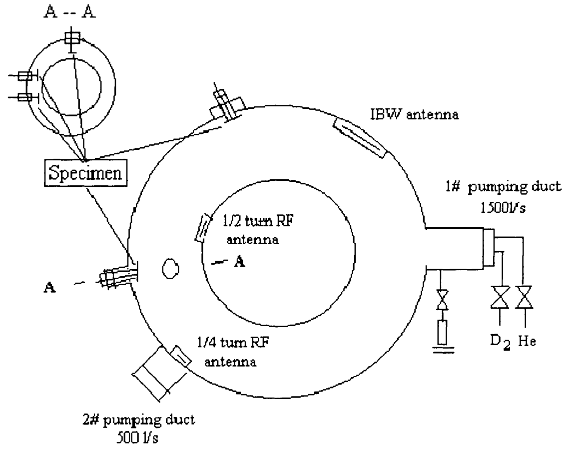

Fig. 1. The layout of the ICRF siliconization system.

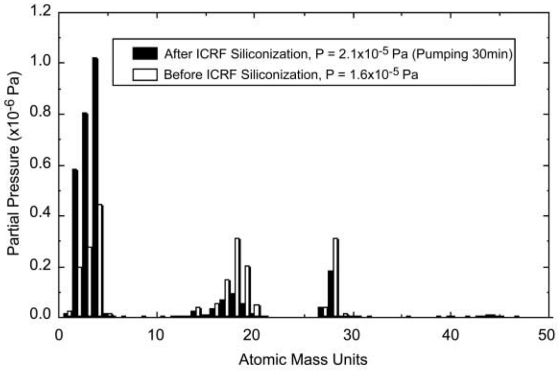

Fig. 2. QMS results before and after ICRF siliconization.

the gas mixture of silane and helium. (2) The delivery line from container to HT-7 vacuum vessel. (3) The valve (PV-10) to control flow rates of the mixed gas. (4) ICRF long antenna located on high magnetic field side, which produces the uniform RF-plasma. (5) A quadruple mass analyzer (QMA) is used to measure the component of residual gas in the vacuum vessel before and after siliconization. (6) Samples with different substrates (molybdenum, stainless steel) were set into separate places of the machine.

For ICRF siliconization, the vessel is filled with silane (SiH_4) is diluted by more than 90% of helium (He) up to a total pressure of $2\text{–}8 \times 10^{-2}$ Pa. The toroidal magnetic field is about 1.5–1.8 T, and the power of ICRF, 8–15 kW. The long antenna located at high field was used, which produced uniform ICRF plasma. Prior to siliconization ICRF discharge cleaning with helium was applied in order to clean the wall, which was very helpful to obtain better adhesion of film. After discharge cleaning, the silane gas mixed with helium was induced into the HT-7 tokamak under the RF plasma in order to carry out the siliconization. The injected gas molecules are decomposed into silicon and hydrogen. Silicon was deposited on the first wall of the device, forming silicon film. The proceeding for siliconization lasted 30 min to 1 h. To improve the deposition of silicon film of high quality, the liner temperature was kept at 200°C. The film thickness was about 20 nm and could last for nearly 100 discharges. With higher filling pressure of 0.06 Pa, the thickness is about 60 nm. The effect of siliconization can still be observed after 300 shots.

ICRF plasma parameters were measured by different diagnostics. The hydrogen ion temperature is 1–2 keV, which was obtained by a neutral particle analyzer (NPA) with a high-energy tail up to several tens of keV. The ion temperature is a very important parameter because it governs the energy of the silane ion that impacts the wall, and it also plays an important role in getting hard film. Plasma density measured by Langmuir probe is in the range of $0.5\text{–}3 \times 10^{17}$ m^{-3}. The electron temperature, estimated from visible line spectrum and ECE, is in the range 3–10 eV within an injection power of 10–30 kW.

The residual gas analysis (RGA) was carried out before and after siliconization. H_2O and CO (mass numbers 18 and 28) are reduced by more than three times, as shown in Fig. 2. Very effective C and O impurities cleaning capability was demonstrated.

3. Analysis of properties of the film

Silicon is a good oxygen getter, and has a large sticking probability on the wall surfaces. The bond energy per oxygen is 428 kJ/mol and lies between those of boron (397 kJ/mol) and beryllium (581 kJ/mol). Thus silicon is expected to provide good control of oxygen impurity. Silicon coating is non-abrasive, scratchproof and does not spall off when the substrate is strongly bent. They adhere very well to all substrates. All deposits show bright interference colors indicating their semi-transparent. The thickness of the Si:H fresh film is about 60 nm, the Si/C ratio is around 1–2. Silicon mainly bonds with carbon. After exposure to tokamak discharges, the Si–O bond increased by a factor of 3, a higher efficiency in gettering O^+ of α-Si:H films is observed. The silicon layer has a well-defined composition, which is homogeneous and amorphous, as seen from depth profile of constituents of siliconization layers in stainless steel specimen, shown in Fig. 3(a). The silicon coating and the bonding states of elements have been studied by X-ray photoelectron spectroscopy (XPS). Fig. 3(b) shows the XPS spectra of Si (2p) and C (1s) core level in different layer of a-C/Si:H film. It is shown

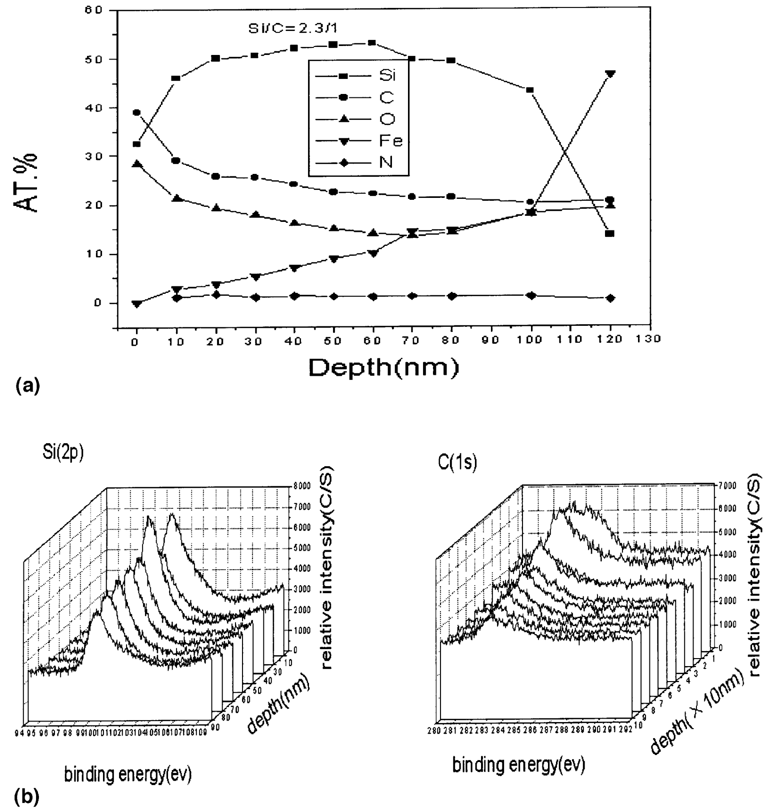

Fig. 3. (a) XPS analysis of composition of the silicon film and (b) XPS spectra of Si (2p) and C (1s) core level in different layers of film.

that the binding energies of Si and C bound in pure silicon, graphite, SiC and SiO_2. Both Si (2p) and C (1s) present a peak maximal at binding energies dense to those of these elements bound in SiC. No shoulders or humps are present at energies, which would point out C–C, Si–Si and Si–O bonds.

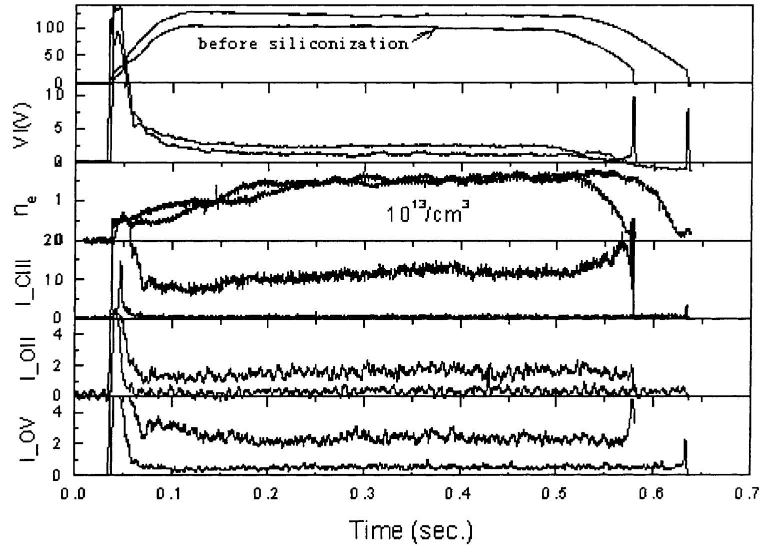

Fig. 4. Comparison of two discharges before and after siliconization.

4. Plasma performances improvement

The better plasma discharges were obtained after ICRF siliconization in HT-7 superconducting tokamak. Fig. 4 shows comparison of two discharges before and after siliconization. Decreased loop voltage and increased plasma current were achieved at same line averaged electron density. It is a direct result of reduced impurity levels. A weak, hollow and broader electron density and electron temperature profiles were formed; higher electron temperature was obtained for the same plasma current and density (Fig. 5).

The impurities and radiation power were reduced greatly, as shown in Fig. 6. The light impurities (C and

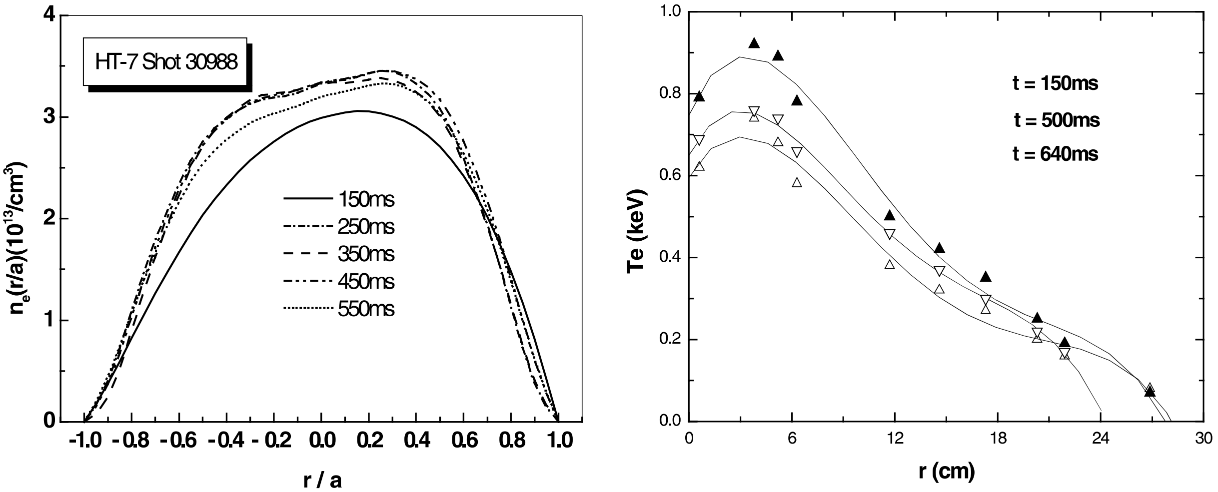

Fig. 5. A weak, hollow electron density and broader electron temperature profiles.

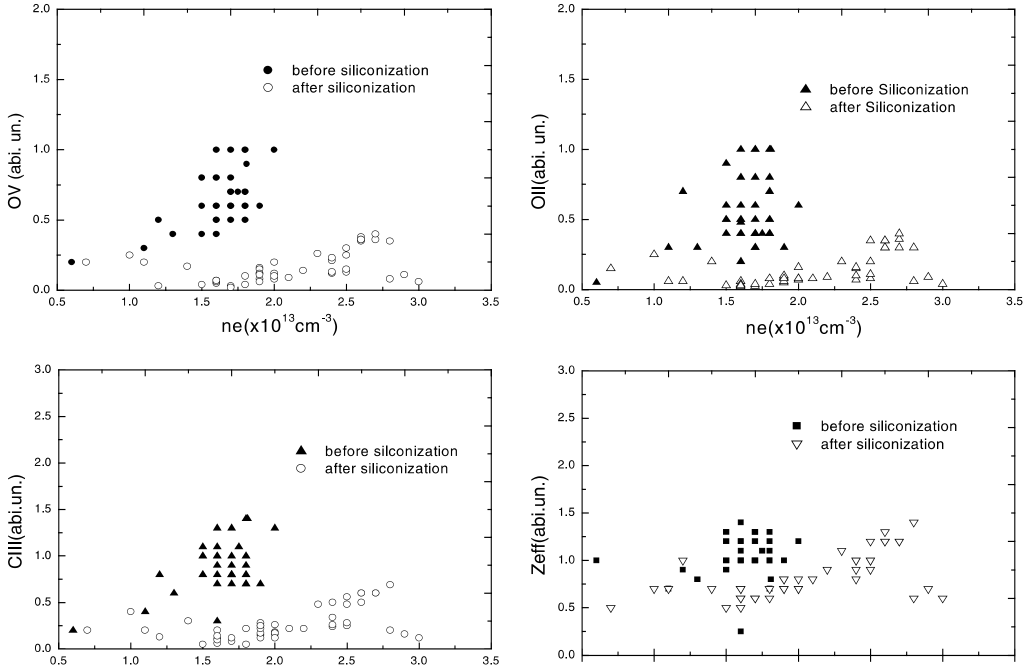

Fig. 6. The impurities reduced significantly, C and O by a factor of more than 2.

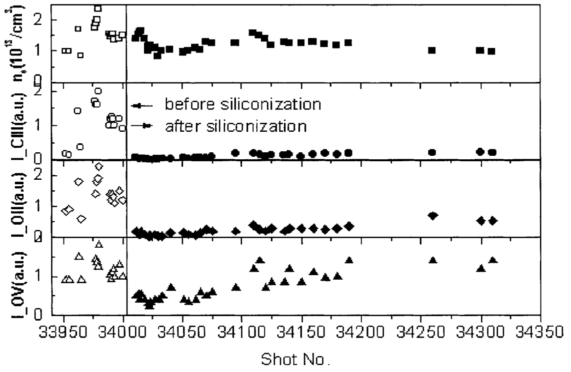

Fig. 7. Impurity levels as a function of shot number after siliconization.

O) are reduced by a factor of more than 2, metal impurities by a factor of more than 3. The radiation power is significantly dropped on the condition of the same plasma current and density ($I_p = 120$–160 kA, line average density 1.5–2×10^{19} m^{-3}). The metal released from the first wall is suppressed because of the coverage of the structure material and its protection by the coating. Fig. 7 shows the behavior of plasma impurities shot by shot after siliconization. It is clearly seen that the effect of siliconization lasts for more than 100 shots in sense of impurity suppression. Lower q and extended operation limit were achieved. The edge safety factor could be as low as 2.45, and reproducible shots were obtained easily.

5. Comparison with boronization

Compared to the boronization, plasma discharges after the siliconization are characterized by a further reduction of low-Z impurities in the plasma (B, C, and O). It showed much faster transit from leak of air to good wall condition. Discharges were back to a good state, and easy recovery from the disruption has been observed. This is attributed to the control of oxygen impurities. The recycling could be easily handled after siliconization without the need of further ICRF processing. The ICRF siliconization was also used intensively not only to get low hydrogen recycling, but also to obtain the enhanced performance of reproducible plasma discharges. On the other hand, the lifetime of the silicon film is shorter than that of boron film. The uniformity of the film is as good as boron one.The possible reason for much thinner silicon film is due to the low ratio of helium to silane gas. Higher silane content in the working gas will be beneficial for higher film thickness.

6. Summary

The ICRF siliconization technique has been developed in HT-7 superconducting device, which is the first try in a tokamak. It was proved to be a very effective, powerful, quick and in-time wall condition method. This technique is aimed at future large superconducting devices in the presence of high magnetic field. The Si/C:H films show higher adhesion, uniformity than those obtained by normal GDC method. The impurity level is reduced significantly after siliconization. Better plasma performance was obtained after ICRF siliconization.

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