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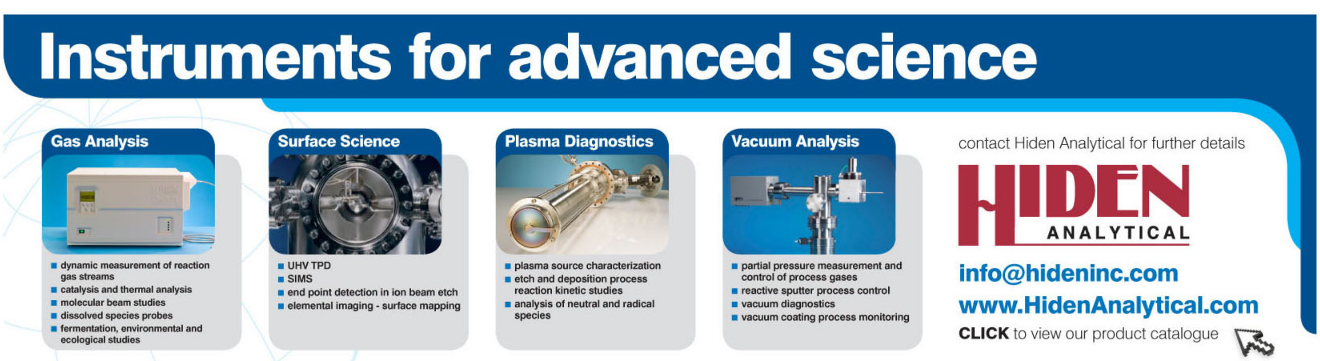

The effects of radio frequency waves on the sputtering of ion cyclotron resonance heating antenna Faraday shields

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The sputtering of the graphite covered Faraday shield of an ion cyclotron resonance heating loop antenna has been studied. The antenna operated at 50 MHz and was exposed to a weakly magnetized plasma produced by the High Particle Flux Facility at Oak Ridge National Laboratory. The flux at the antenna was on the order of 3×10^{17} cm^{-2} s^{-1}. A dc bias voltage applied to the antenna allowed the effective energy of the impinging hydrogen ions to be varied up to 65 eV. Coupled rf power varied from 0 to 3 kW. Sputtering depths were directly measured by surface topography. Sputtering enhancement due to rf was between a factor of 2 to 4, depending on the position along the antenna. Antenna voltage profiles were calculated and used to correlate measured erosion coefficients with ion energies. Various sputtering theories and possible chemical sputtering effects are discussed.

I. INTRODUCTION

An important issue in fusion research is the interaction of the plasma with the containment vessel and its components. These interactions, particularly physical sputtering, can affect the plasma edge characteristics and the energy confinement, as well as the generation and control of impurities.[1]

One important aspect of these plasma-surface interactions is the effect of radio-frequency heating on the sputtering of ion cyclotron resonance heating (ICRH) antenna components. Several rf experiments on various fusion machines have shown an increase in the impurity concentration due to the effects of ICRH. Experiments on the Princeton Large Torus (PLT) showed that there was an increase in the impurity concentration coming from the Faraday shield during the launching of rf waves.[2] Experiments also showed an increase in the total neutral efflux by a factor of 5 with rf power levels on the order of 2 MW. The rf appeared to increase the radial transport of the plasma, causing an increase in the edge density and an increase in the sputtering.[3] In the TCA and TFR tokamaks, the density gradient decreased during rf which caused an increase in the edge ion density as well. The electron temperature in this region also increased from 8–10 to 15–30 eV. This temperature rise caused an increase in the plasma sheath potential which, in turn, increased the energy of the ions falling through the sheath and led to an increase in the sputtering.[4]

To study the effects of rf on the sputtering of ICRH antenna Faraday shields, an experiment was performed on the High Particle Flux Facility (HPFF) at ORNL. The HPFF was chosen because its plasma parameters are similar to that of the edge plasma of a fusion device ($T_e \approx 6$ eV, $n_e \approx 3\times10^{11}$ cm^{-3}), which is the environment where an ICRH antenna may operate.

A total of five different experiments were performed involving combinations of effective ion energies and rf power levels. Non-rf experiments included one with the antenna grounded and one with a -30 V dc bias on the antenna to give the incident ions a higher effective energy. The rf experiments included one with the antenna grounded (2.2 kW coupled), one with the antenna floating (2.8 kW coupled), and one with a negative dc bias on the antenna (3.0 kW coupled). Yield results are calculated for these experiments and compared to theoretical/empirical sputtering models.[5–8]

II. APPARATUS

A schematic of the experiment is shown in Fig. 1. The plasma source was an ORNL duoPIGatron originally developed for neutral beam injection. The source chamber had dimensions of $56\times30\times30$ cm. The test chamber with the antenna was made of copper with dimensions $56\times30\times23$ cm. The source produced a hydrogen plasma with an ion fraction $H_1^+:H_2^+:H_3^+$ of approximately 80:15:5.[9,10] The plasma was pulsed for 400 ms every 10 s.

The antenna used was a simple magnetic loop cavity antenna 35 cm long and 6.67 cm wide, with a 1.59-cm-wide current strap. The antenna was mounted into the side of the test chamber with a Teflon flange to allow the antenna to be electrically isolated from the test chamber. The Faraday shield was slotted copper, with Poco graphite strips attached to it between the slots. The graphite strips ($6.67\times0.81\times0.15$ cm) were polished and ultrasonically cleaned before being bolted to the Faraday shield. At three locations along the antenna, the graphite strips had two masking materials (nickel and graphite) placed on them so that the graphite strip was partially covered. After the graphite strips were exposed to the plasma, the masks were removed to show an area of noneroded graphite. The amount of erosion could be calculated by measuring the difference in height between the noneroded and eroded areas.

The antenna flange had three diagnostic feedthroughs. One was located 1 cm in front of the antenna and was used for a Langmuir probe (10-mil tungsten wire) so that the plasma parameters could be measured along the antenna. The other two feedthroughs were used for thermocouples.

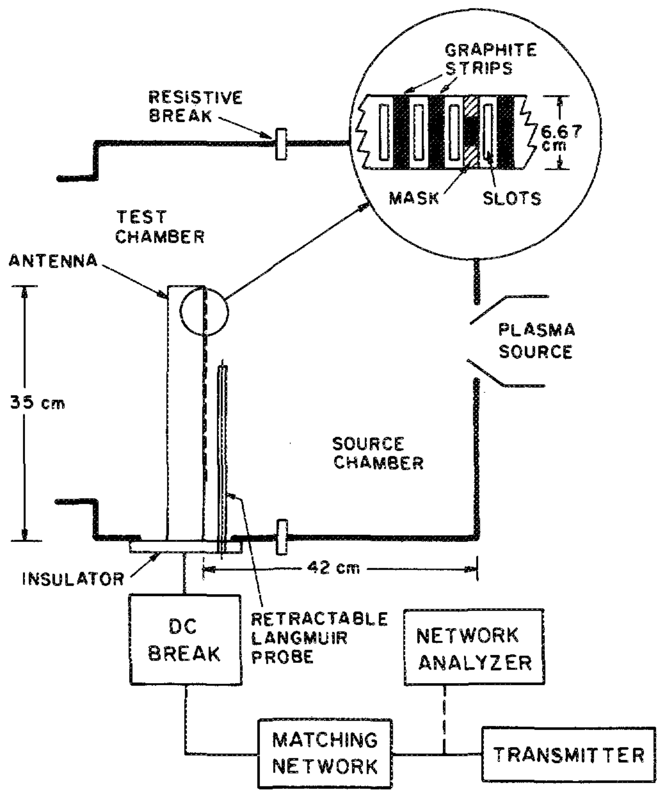

FIG. 1. Schematic of the apparatus showing the antenna position in the test chamber and the graphite strip arrangement on the Faraday shield.

One thermocouple was placed 30.5 cm from the flange on the back of the antenna and the other was placed on the Faraday shield, 2.4 cm from the shorted end of the antenna.

The 50-MHz rf system was composed of a transmitter, a network analyzer, a tuner, and a dc break. The network analyzer was used to measure the antenna loading during a plasma shot, so that the antenna could be matched. A single-stub tuner with a phase shifter was used for matching. A dc break was used in some experiments to allow the antenna to be at a dc voltage independent of the test chamber during an rf pulse.

III. ANALYSIS

An example of the difference in height between the noneroded and eroded regions of one of the graphite samples is shown in Fig. 2. These data were taken by digitizing the output of a Tencor Alpha-Step™ Surface Profiler. The large spike at the interface region is due to the redeposition of eroded material. The erosion depth was calculated by fitting a line through the data points in the eroded and noneroded regions (solid lines in Fig. 2). The perpendicular distance between these lines was taken to be the erosion depth. The error in calculating the slope and intercept of the lines was used to provide the error in calculating the erosion depth. The erosion depths in the experiments varied from 0.27 ± 0.07 to $1.11 \pm 0.09\,\mu$.

The erosion yield was calculated by using

$$\text{Yield} = (\text{erosion depth/ion influence}) \times N_{\text{gra}}, \quad (1)$$

where $N_{\text{gra}} = 9.24 \times 10^{22}$ atoms cm^{-3}, the number density of the graphite, and the ion fluence is

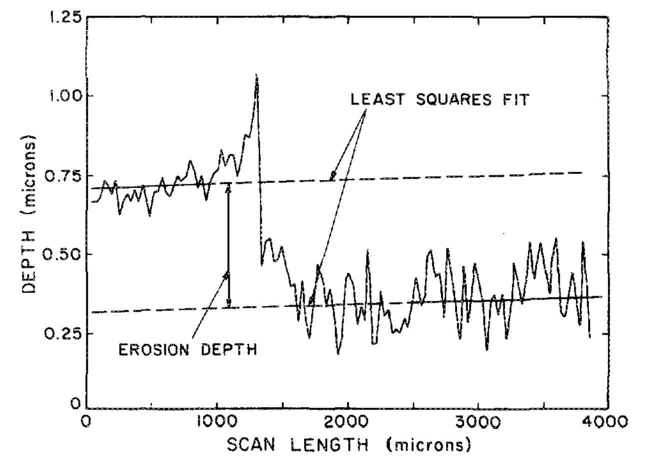

FIG. 2. Typical surface profile of a sample showing the difference in level between the eroded and noneroded areas. Erosion depth is determined by the perpendicular distance between the two lines.

$$\text{Fluence} = I_{\text{sat}} \times (\text{ion charge})^{-1} \times t / A_p, \quad (2)$$

where I_{sat} is the ion saturation current measured with a Langmuir probe and t is the total time that the sample was exposed to the plasma. The probe area A_p was calculated by assuming that the effective radius of the probe was the geometric radius of the probe (0.0127 cm) plus 2.3 times the Debye length ($l_d = 3.3 \times 10^{-3}$ cm). The fluence varied from $(2.7 \pm 0.1) \times 10^{20}$ to $(3.9 \pm 0.1) \times 10^{20}$ cm^{-3}.

IV. RESULTS

The voltage distribution of the antenna was calculated by a distributed impedance model. The voltage was found to rise linearly from the shorted end of the antenna to the current feed. For the experiments with 2.2, 2.8, and 3.0 kW of rf, the voltages (peak) at the feedthrough were 1500 ± 77, 1690 ± 83, and 2420 ± 210 V, respectively. The respective load resistances were 1.25 ± 0.1, 1.25 ± 0.1, and 0.65 ± 0.1 Ω.

The temperature of the antenna in the non-rf experiments remained fairly steady: around 100 °C for the grounded experiment and 78 °C for the experiment with the − 30-V bias. The Faraday shield temperature was about 10° higher than the antenna. The temperature of the antenna in the rf experiments ranged from about 130 to 200 °C, with the Faraday shield generally 30 °C higher.

The electron temperature, the ion saturation current, and the electron density decreased along the antenna in the non-rf experiments. The electron temperature dropped from about 6.4 ± 0.1 eV at the center of the discharge to 5.3 ± 0.1 eV in a 15-cm distance, while the ion saturation current dropped from about 1.2 ± 0.04 to 0.85 ± 0.03 mA, and the density decreased from $(2.9 \pm 0.1) \times 10^{11}$ to $(2.3 \pm 0.1) \times 10^{11}$ cm^{-3}. The plasma potential essentially remained constant (≈ 30 eV). In the rf experiments, the electron temperature increased to about 10.8 ± 0.4 eV at the center and dropped to 7.8 ± 0.4 eV at a distance of 15 cm. The ion saturation current and the electron density remained approximately the same.

To look at the contributions of particle redeposition, an Auger electron analysis of the graphite strips was attempted.

The only sample for which this measurement worked was the sample located 9.6 cm from the shorted end of the antenna from the rf experiment in which 2.2 kW of rf was coupled. Data from other samples could not be taken because of charge buildup on the surface of the samples due to the electrons from the electron gun of the spectrometer. This charge buildup could be caused by a thin, nonconducting film on the surface of the samples or because of poor electrical contact with the sample holder. However, neither brief sputtering of the sample nor firm clipping of the sample to the Auger carousel improved this situation. The repercussions of this nonconducting nature are discussed in Sec. V.

The results of the Auger analysis showed only C and O present in the masked area. At the interface and in the eroded area, C, O, N, Cl, S, and Cu were found. No significant Ni contamination from the masks was found. The Cu came from the antenna and/or the test chamber. The concentration of Cu on the surface is too small to account for significant sputtering. However, the presence of Cu on the surface could influence the sputtering yield. It has been shown that this presence has the effect of decreasing the sputtering due to chemical effects.[11]

The erosion results are shown in Fig. 3. The yields shown for the rf experiments are those due to only rf effects. The erosion effects when the plasma source was running without the rf operating have been subtracted out, based upon the results from the non-rf experiments. The yield coefficients for the non-rf experiment with the − 30-V bias (● in Fig. 3) was higher than those from the non-rf experiment with the antenna grounded (■ in Fig. 3). This result was expected because of the higher effective ion energy due to the bias. The yield coefficients for the rf experiments (open points) were generally higher than those for the non-rf experiments. The effect of the rf was to enhance the erosion by a factor of between 2 and 4. This enhancement could be caused by an increase in the effective ion energy (hydrogen as well as impurity ions) or possibly by chemical sputtering effects.

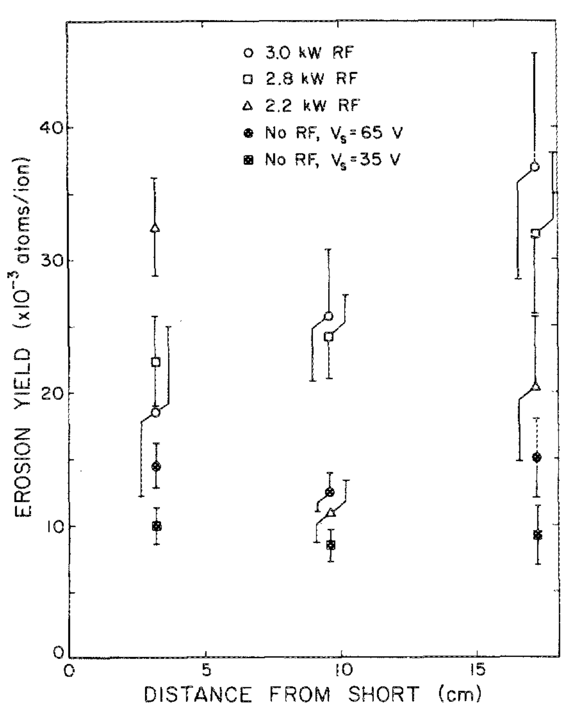

FIG. 3. Erosion yields for the experiment as a function of radial distance from the shorted end of the antenna. The yield generally increased with rf voltage on the antenna.

V. DISCUSSION

If the graphite on the Faraday shield acted as an insulator, a negative dc bias with respect to the plasma potential will develop, due to the applied rf voltage.[12] Evidence for this insulating effect is that the only sample that conducted the Auger spectrometer's electron beam is the sample that did not show the same enhancement of the sputtering coefficient due to rf (△ at 9.6 cm in Fig. 3). Therefore, to model the energy of the ions during rf, a negative dc bias voltage that had the same shape as the rf voltage profile was assumed to exist along the antenna. Calculations[13] have shown that the magnitude of this negative dc bias is equal to about half the peak-to-peak voltage of the applied rf signal. The percent of this voltage that exists on the surface of the Faraday shield is not known. To compare the results with various sputtering theories, the value of the voltage on the surface of the Faraday shield was taken to be the same as the voltage on the current strap. This choice represents the upper limit of the value of the surface voltage. When the non-rf sheath potential was added to this value, the energy of the incident ions could be estimated. The results are shown by the solid data points in Fig. 4.

For the conducting sample, the average energy of these ions can be approximated as the average value of a half-cycle of the rf voltage, which is $2V_{\text{peak}}/\pi$. Since the ions only bombarded the Faraday shield one-half of the time, the ion fluence on the antenna was one-half that used to calculate the yield. Therefore, the effective yield is twice that shown in Fig. 3. Taking the value of the peak voltage at that point on the antenna, the yield can be represented by the open circle

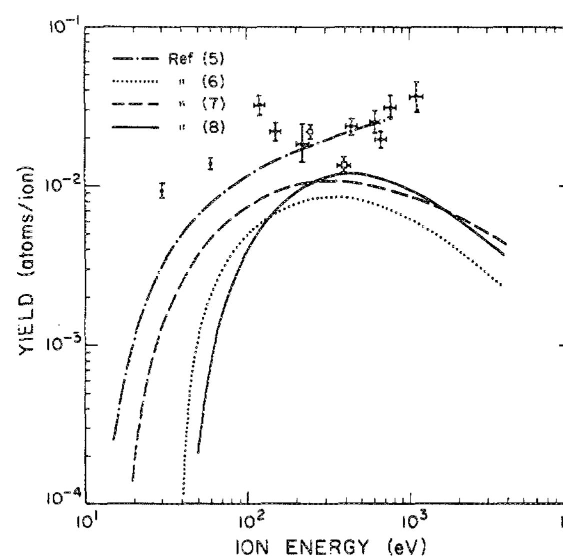

FIG. 4. Experimental data points shown with various sputtering formulas. The two lowest energy points are from the non-rf experiments. The ion energy represented for the rf experiments is the upper limit for the voltage on the Faraday shield. The open box and circle are two different treatments of the only conducting sample.

in Fig. 4. If the sample had acted as an insulator, the result is that shown as the open square on Fig. 4. The yields calculated from Refs. 5–8 are also shown in Fig. 4. The most obvious difference between the equations is in the value of the threshold energy for sputtering.

To check the energy of the hydrogen ions impinging on the surface, a secondary ion mass spectrometry depth profile was performed. An implant profile was observed; however, the expected depth of penetration (<100 Å for ion energies <1 keV)[14] was on the same order as the surface roughness, and no energy estimates could be made.

Chemically enhanced sputtering could help account for the high erosion yield. A change in surface composition due to ion irradiation has the effect of lowering the binding energy.[15] For hydrogen ions impinging on a carbon target, hydrocarbons such as methane form on the surface and are emitted. The enhancement due to chemical effects is strongly temperature dependent and has a maximum erosion between 700 and 900 K.[15] The temperature of the samples in the experiment ranged from around 385 K for the non-rf experiments to around 500 K for the rf experiments. Even though these temperatures are less than the temperature where the maximum occurs, the possibility of the enhancement is still important.[11]

VI. CONCLUSIONS

The purpose of this study was to determine the effects of rf on the sputtering of ICRH antenna Faraday shields. The results indicate that the sputtering is enhanced by up to a factor of 4 for the rf power levels used. This enhancement can be due to the ions being accelerated by the rf voltage on the antenna and also due to enhanced chemical sputtering effects. Studies in current fusion devices are needed to expand upon these results.

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