Low-temperature plasma removal of deposits from fusion first mirrors

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Abstract

Within a fusion device the optical component closest to the plasma is called the first mirror. With the device in operation the high energy atoms within the plasma erode the plasma facing material and redeposit it around the reactor. Mirrors suffer this erosion and re-deposition process and it causes degradation in the quality of the signal reaching the diagnostics. Erosion is easily overcome with single crystal or small scale crystal structures but the deposition is substantial and with no easy solution [1].

The proposed method of removal of these deposits is using a low-temperature plasma in-situ, but outside fusion operation, in order to maintain reflectivity. This involves creating a capacitively coupled plasma using the mirror itself as the powered electrode. Experiments have been carried out to test this method and they have yielded good results [2]. Due to the toxicity of the beryllium used in the construction of the first wall the majority of experiments have used aluminium oxide as a proxy. It is only recently that experiments using beryllium deposits have been conducted, and in limited numbers. In order to improve the removal process it has become prudent to use computer simulations. The Hybrid Plasma Equipment Model has been used in order to investigate and optimise the deposition removal process through simulating conditions and chemistry as close to the working environment as possible.

Introduction

First mirrors on ITER and other fusion devices will be stainless-steel, molybdenum, or rhodium coated molybdenum [3]. These first mirrors are essential for diagnosing the plasmas that will be created in such machines for both research and real time control. As access to these mirrors will be impossible during a fusion campaign as they are tightly encased within the vacuum vessel an in-situ method of deposition removal is required.

Plasma etching is a well known industrial process used significantly in the manufacture of computer chips [4]. By forming a plasma above a material, and inducing a negative bias on that surface, the ions of the plasma can impact the material with sufficient energy to displace and eject surface atoms. In the case of aluminium oxide the impact energy of an argon ion required to sputter is 50 eV [5]. Data for sputtering energies of beryllium are limited and no data exists for the energy required for an argon ion to sputter beryllium oxide. Data does exist for beryllium sputtering in deuterium with threshold energies of 10 eV and 29 eV for beryllium and its oxide respectively. When comparing this with aluminium (36 eV) and its oxide (66 eV) it is clear that it takes significantly higher energies [6].

The model used in this work is the Hybrid Plasma Equipment Model (HPEM) [7]. This is a 2D modular code that combines fluid and kinetic approaches. Within HPEM the conservation of mass, momentum, and energy equations are solved alongside Poisson's equation for the electric potential. This is done for ions and neutral particles. Due to the phenomenon of non-local electron heating at low pressures the electrons are addressed through a kinetic Monte Carlo approach. Electron collision rates are input to the code and a process of stochastic collisions though multiple iterations is completed to gather statistics to output transport coefficients. The gas phase reaction mechanism for the Ar/O/Al plasma contains 28 species and 401 reaction processes and the frequency is 13.56 MHz.

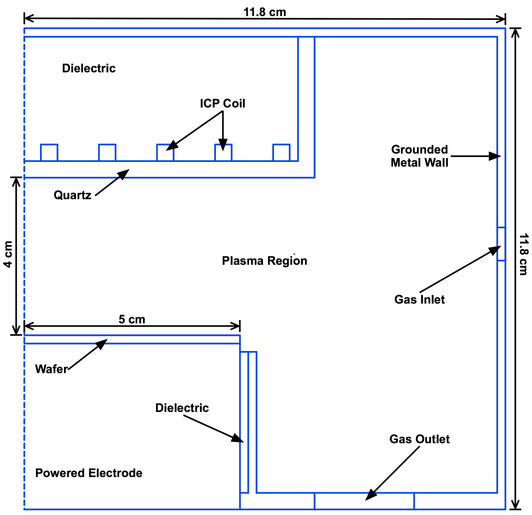

Figure 1: *HPEM model geometry*

The model geometry used in this work is a proxy of the experimental geometry used at York and is shown in figure 1. This geometry includes an inductive upper electrode that is present in the York device as it is also used to deposit thin films including aluminium oxide for this etching work. This coil is grounded in the simulation and during capacitive operation in the experiment. The area defined as the wafer is the deposited aluminium oxide to be etched.

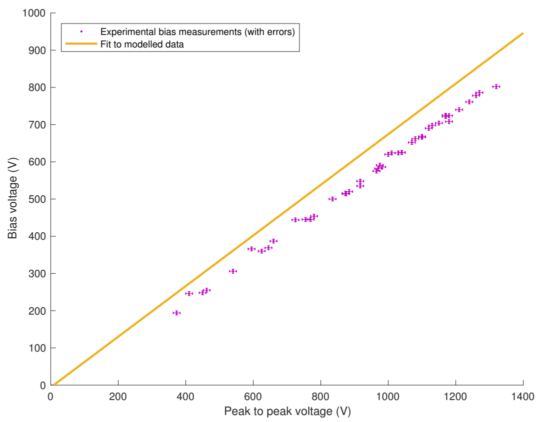

Figure 2: *Electrode bias in experiment and simulation. All model data points lie on the fitted line.*

Results

The most important parameter for ion impact sputtering is the ion impact energy which depends, in part, on the bias of the driven electrode. The peak ion energy will be at a combination of the plasma potential and the bias voltage. When comparing the model and the experimental bias a difference exists as is shown in figure 2. For reference; the experimental data was taken at multiple pressures between 20 mTorr and 60 mTorr, the simulated pressure was at 50 mTorr. In this figure the bias in the experiment is shown to be significantly lower than that produced within the model at all input voltages with the two diverging towards higher potentials. This can be explained through a difference in the grounded to driven areas. In the model the grounded walls are much closer than in the experiment as the size of the simulated area directly impacts the efficiency of the code. Within both of the geometries the plasma does not "see" the full grounded area due to the distance and slight asymmetries in the experiment which cannot be reproduced in a symmetrical coordinate system. Thus the ratio of driven to grounded areas is smaller in experiment than in the model which subsequently causes a lower bias [8].

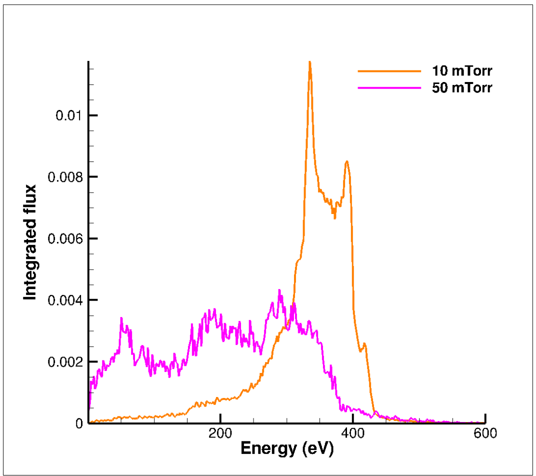

Figure 3: *IEDFs for 10 and 50 mTorr at an RF potential of 400 V*

The ion impact energies predicted by the model at varying pressures are shown in figure 3. The higher the pressure the more collisional the plasma becomes and thus the ions are unable to accelerate to higher energies before collisions occur. This is clear from the classic saddle structure of the 10 mTorr line in which the two peaks come from the increased density of ions at either edge of the sheath. It is unknown at what pressure the implementation of this system will have on ITER. It is clear that the lower pressures, assuming successful ignition of the plasma, will produce the most efficient energies for etching. In figure 3 the shift of the energies along the x axis is due to the bias of the driven electrode.

Conclusion

On ITER the mirrors and their surrounding areas will differ substantially. It is therefore impossible to design an experiment that will sufficiently predict the required parameters for any plasma etching method to work in all cases. There is also a consideration that ion energies that sputter the oxide deposits will potentially have enough energy to etch the mirrors themselves. This makes it important to adjust the parameters to a case where minimal mirror damage is possible while still removing the deposits. It is more reasonable to model the varying mirror geometries and successfully predict the most efficient etching parameters.

Acknowledgements

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References

[1] A. Costley, T. Sugie, G. Vayakis, et al., Fusion Engineering and Design **74**, 74 (2005)

[2] L. Moser, R. Steiner, F Leipold, et al., Journal of Nuclear Materials **463**, 463 (2015)

[3] Donne, A. J. ., Costley, A. ., Barnsley, R., Bindslev, H., Boivin, R., et al.,Nuclear Fusion, **47**(6) (2002)

[4] Donnelly, V. M., Kornblit, A. Journal of Vacuum Science & Technology A, **31**(5) (2013)

[5] Lee, Y. H., Zhou, Z. H., Danner, D. A., et al, Journal of Applied Physics, **68**(10), (1990)

[6] A. Razdobarin, et al., Nuclear Fusion, **55**(9) (2015)

[7] M. J. Kushner., Journal of Physics D: Applied Physics, **42**(19) (2009)

[8] Lieberman, M. A., & Lichtenberg, A. J., Principles of Plasma Discharges and Materials Processing (2005)