Ion energy distributions in dual frequency RF plasmas

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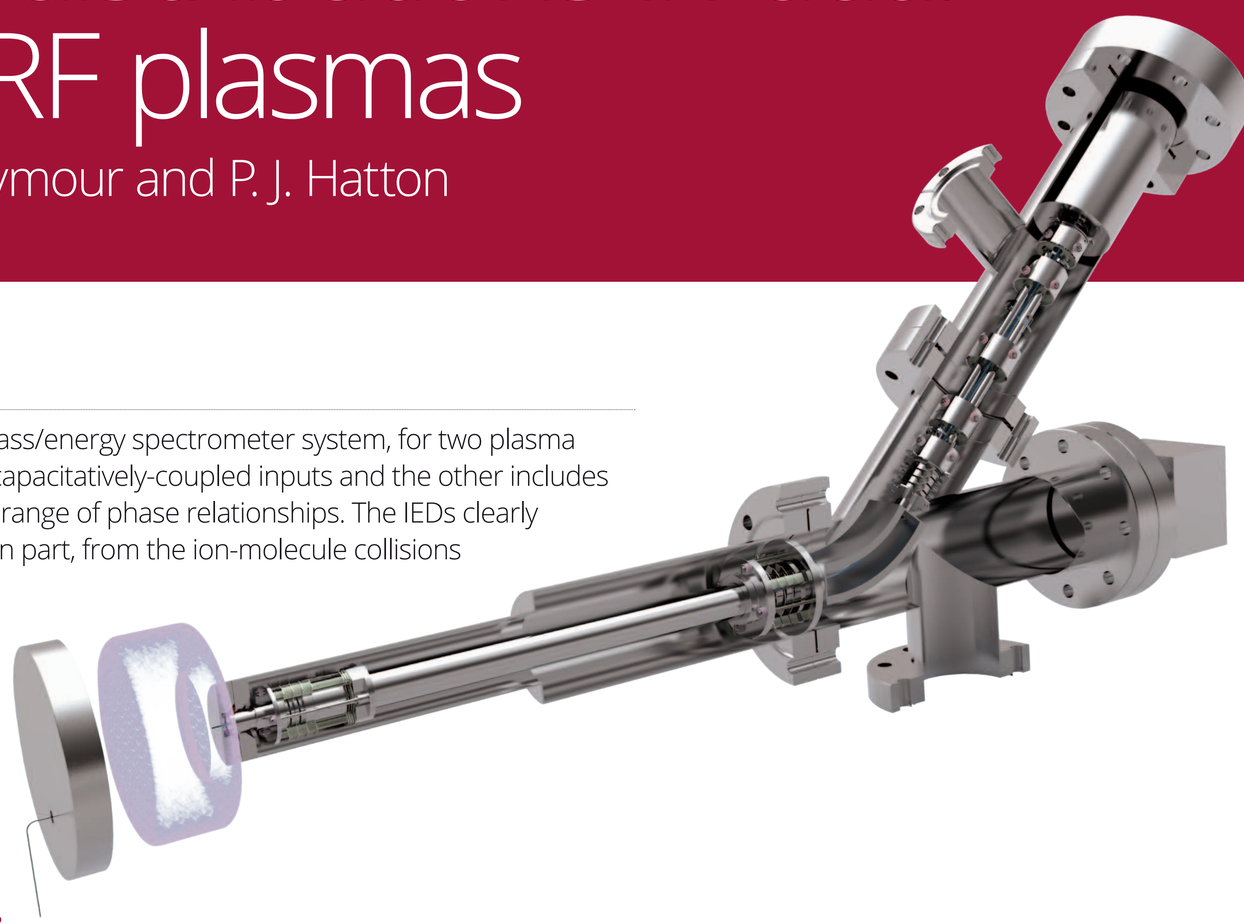

Abstract:

Ion energy distributions (IEDs) for both positive and negative ions have been measured, using a mass/energy spectrometer system, for two plasma reactors which can be operated using a combination of two RF power sources. One reactor uses capacitatively-coupled inputs and the other includes an inductively-coupled input. Typical data for 2.26, 13.56 and 27.1 MHz inputs are presented for a range of phase relationships. The IEDs clearly show significant differences between the data for different species of ions. The differences result, in part, from the ion-molecule collisions occurring particularly in the plasma/surface sheath regions.

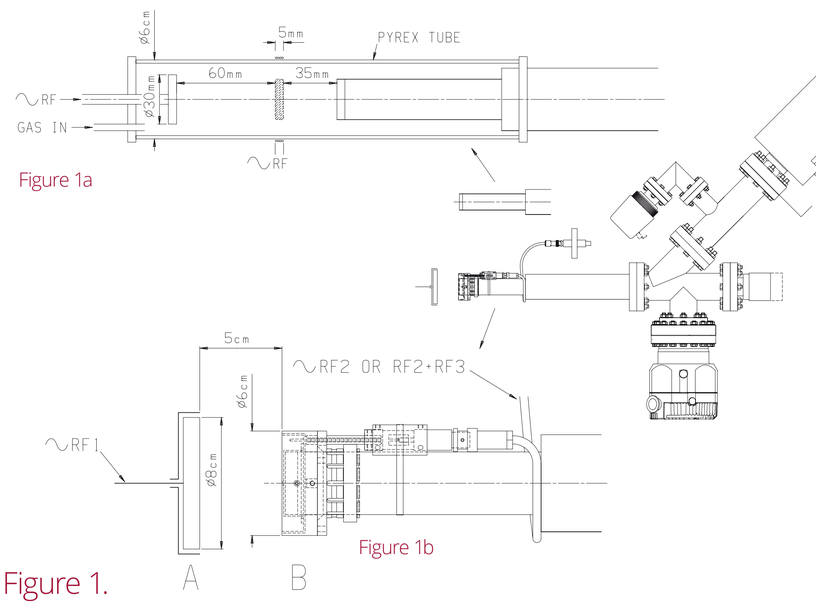

Figure 1.
Plasma reactors

Introduction:

For many surface-processing applications involving plasmas operated at RF frequencies it is helpful to combine two sources of power operating at different frequencies. By choosing suitable input powers at the two frequencies and varying the phase relationship set between the two inputs, the energy distributions (IEDs) for the ions arriving at the target surface can be optimised. Only a few reports such as that of Coumou et al.[1],in which the energies of the ions arriving at th e powered electrode were measured using a gridded analyser, have been published. More recently, Zhang et al.[2] have modelled ion energy distributions for dual frequency plasma reactors. We have measured using a Hiden mass/energy EQP analyser [3] the IEDs for ions in plasmas generated in two reactors using combinations of 2.26, 13.56, and 27.12 MHz. The distributions were measured for known species of ions and show strong differences which are controlled not only by the mass and charge state of the ions and their formation processes but also by the ion/molecule collisions occurring in the plasmas.

Figure 2.
IEDs for argon plasma at 20 mTorr with 13.56 and 27.12 MHz using the reactor (Figure 1a) for phase differences 0^o to 180^o.

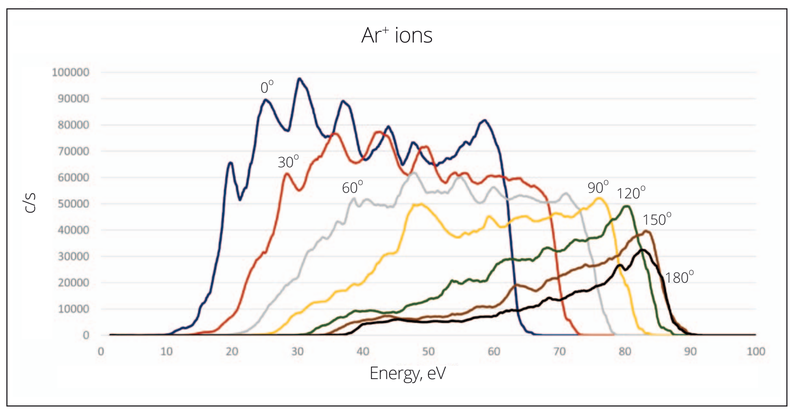

Figure 2a

Figure 3.
IEDs for N^+ ions in nitrogen plasma at 50 mTorr for mixed 2.26 and 13.56 MHz signals for selected phase differences

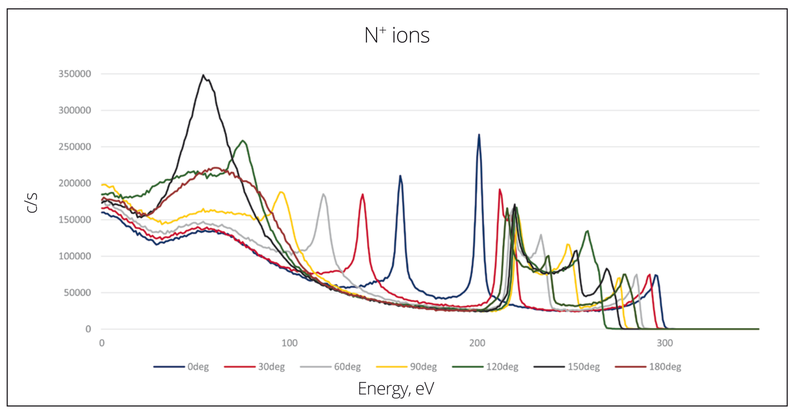

Figure 3a

Figure 4.
IEDs for negative ions in nitrous oxide at selected phase differences

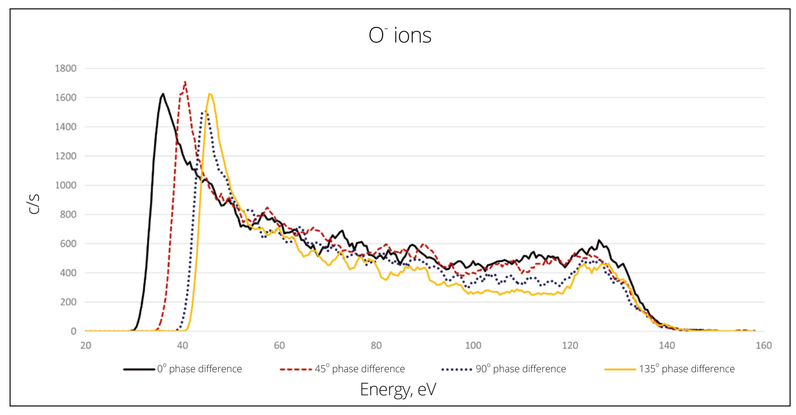

Figure 4a

Comparison of IEDs for N^+, Ne^+ & Kr^+ ions at 345^o phase difference

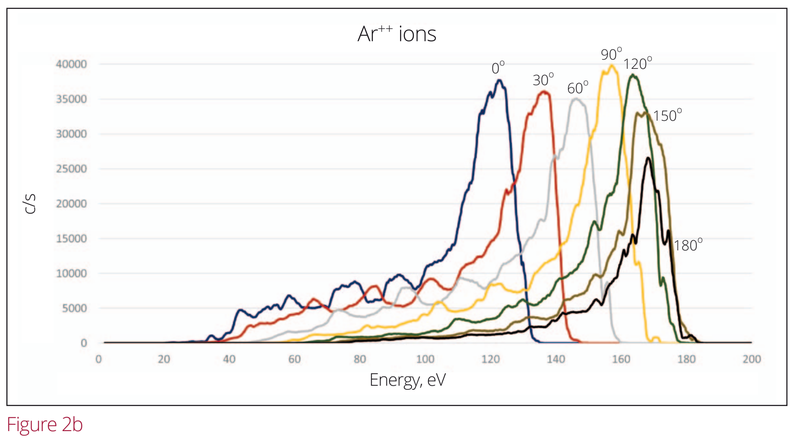

Figure 2b

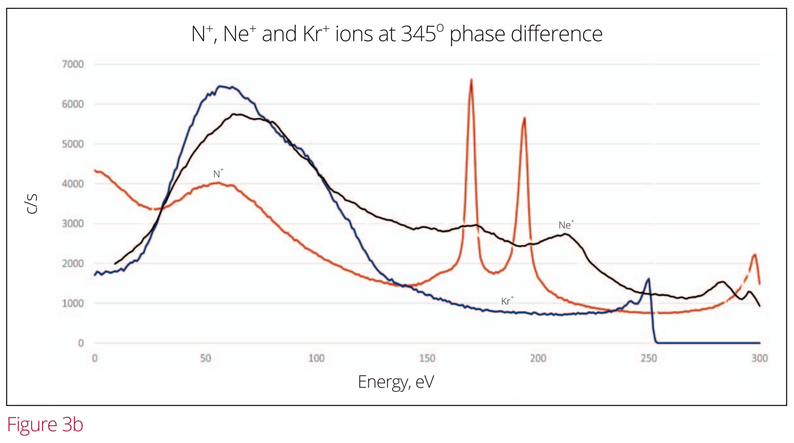

Figure 3b

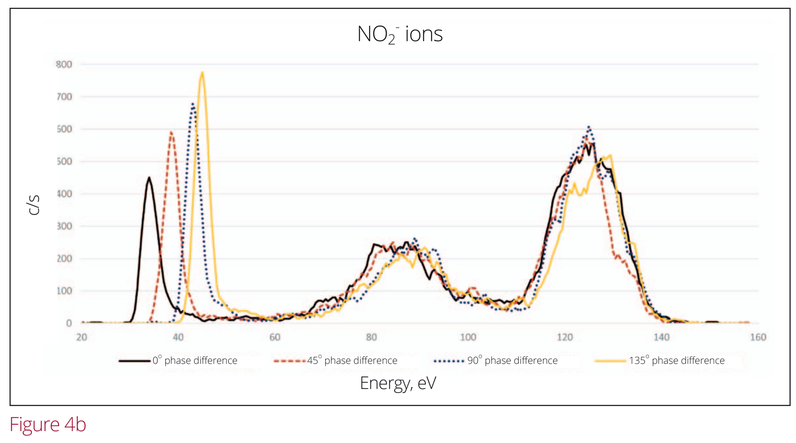

Figure 4b

Experimental procedure and data:

The first reactor used for the present work (see figure 1a) was a cylindrical Pyrex tube (60mm diameter). The plasma was generated at 27.12 MHz using a wire coil of 4 turns over a length of 10mm around the central section of the tube. The EQP instrument [3] was attached to one end of the reactor tube with its grounded sampling orifice located at a distance of 35mm from the axial position of the centre of the exciting coil. A small disc electrode at the other end of the reactor tube was 60mm from the sampling electrode and was separately powered at 13.56 MHz. IEDs were measured for the ion species reaching the sampling orifice of the EQP. Typical data for singly- and doubly-charged argon ions are shown in figure 2 for a range of phase differences between the two RF supplies. The gas pressure was 20 mTorr and the RF powers were 2 W at 13.56 MHz and 4 W at 27.12 MHz.

In other experiments the arrangement shown in figure 1b was used. The plasma could be generated using various combinations of 2.26, 13.56, and 27.12 MHz applied to electrodes A and B. Electrode B was an integral part of the Hiden mass/energy spectrometer. Typical data are shown in figures 3 and 4. Figure 3 was obtained using plasmas generated in a gas mixture of nitrogen with 2% additions of helium, neon, and krypton, at a total pressure of 50 mTorr with a combination of 2.26 and 13.56 MHz power applied to electrode B with the phase difference between the two supplies varied between 0 and 180 degrees in 30 degree steps. The RF powers were 8 and 3 Watts at 2.26 MHz and 13.56 MHz. Figure 3a shows the ion energy distributions (IEDs) for the atomic N^+ ions at the various phase differences and figure 3b compares the IEDs for N^+ ,Ne^+ and Kr^+ ions at a phase difference of 345 degrees under the same plasma conditions.

With a plasma operated in nitrous oxide at 4 mTorr, using power at 13.56 MHz applied to electrode A and 27.12 MHz applied to electrode B, measurements included those shown in figure 4 for negative atomic oxygen and molecular nitrogen dioxide ions. Sample scans for four phase differences are shown.

Discussion and Conclusions

The IEDs in figure 2 show marked differences between the two species. For the doubly-charged Ar^{++} ions the average energy is double that for the atomic ions and reflects the variation with phase angle of the plasma potential. For the Ar^+ ions, the strong influence of charge exchange collisions in the plasma sheath in front of the EQP leads to large numbers of ions at low energies, particularly at low phase differences. In figure 3a, the IEDs at higher energies show clearly the double peak structure obtained when the transit time of the ions across the sheath in front of electrode B is comparable with the period of the applied RF. Figure 3b shows considerable differences between IEDs for the three ion species, both in their structure and maximum energy which result from differences in the formation processes for the three ion species and in their transport through the whole of the plasma region. Figure 4 demonstrates the EQP's capability to work with negative ions. For the particular conditions of the present experiment, the main effect of the phase variations was seen at the lowest ion energies and is attributed to changes in the sheath region in front of electrode B.

The main conclusion to be drawn from the small sample of data shown here, is that measurements made with the aid of mass/energy analysers give valuable confirmation of the great flexibility of control over IEDs that can be achieved through the use of dual-frequency plasma generation in reactors designed for materials processing and emphasises the need for mass identification of the ion species involved.

References

[1] D.J. Coumou, D.H. Clark, T. Kummerer, M. Hopkins, D. Sullivan, and S. Shannon : IEEE Trans. Plasma Sci. 42 (2014) 1880

[2] Y. Zhang, M.J. Kushner, S. Sriraman, A. Marakhanov, J Holland, and A. Paterson : J. Vac. Sci. Technol. A33(3) (2015) 031302-1

[3] J.A. Rees, C.L. Greenwood, and D.L. Seymour: Jpn. J. Appl. Phys.38 (1999) 4397

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