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STUDIES OF ECR PLASMAS AND MATERIALS MODIFICATION USING LOW ENERGY ION BEAM FACILITY AT IUAC

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Abstract

The ECR ion sources are widely used to produce high intensity of highly charged positive ions. To increase their performance further, several techniques are employed. The addition of a lighter gas into the main plasma (so called gas mixing) shows a substantial effect on the charge state distribution of highly charged ions. Although many theoretical models were used to explain this gas mixing effect, yet it is not fully understood. The low energy ion beam facility (LEIBF) at Inter-University Accelerator Centre (IUAC), New Delhi, India, which comprises of a 10 GHz all-permanent magnet NANOGAN ECR ion source placed on a high voltage platform (400kV) has been used to develop several plasmas for the physical understanding of ions production and their confinement in a strong magnetic field. Further, the LEIBF allows us to extract ion beams from the plasma in the energy range of a few keV to tens of MeV for novel ion-matter interaction experiments. In this paper, the charge state distribution studies (relevant to gas mixing effect) of various atomic species at optimized ion source tuning parameters along with some interesting results on materials modification using ion beams is presented.

INTRODUCTION

The Electron Cyclotron Resonance ion sources (ECRISs) [1] are most suitable for producing high intensity of multiply charged ions and therefore, preferred as an injector in high energy particle accelerators. In fact there exists some ECRIS based implanter/low energy facilities for conducting research in materials science, atomic and molecular physics [2–4]. A cylindrical vacuum chamber consisting of multi-pole magnets around it and two solenoids at its ends, RF power injector and gas feed systems are essential components of ECRIS. The electrons gyrating in a magnetic field gain energy from the input RF wave via ECR and the plasma is formed by the step-by-step electron impact ionization. In the past few decades, a significant progress has been made to enhance the performance, mainly with the better understanding of of plasma and advancement in the magnetic field technology for its confinement. With the frozen design of the source, some additional techniques are also employed to further increase the intensity of highly charged ions. [5].

The gas mixing technique has been found to be very effective to boost the intensity of the highly charged ions in many folds (3-4 times) [6]. In most studies of gas mixing effect, He gas is chosen for lighter masses (such as O, N, Ne etc.), whereas O and N are used for heavier masses (Xe, Ar, Kr) [3, 7–12]. However, till now, there is no empirical rule for selecting a suitable gas for mixing purposes in a specific system. The gas mixing effect is mainly explained by the ion cooling model [13] and lowering a plasma potential [14]. These two processes decrease the ion temperature resulting a longer confinement time. However, a numerical simulation performed by Mironov et al. [15] showed that the ion temperature (T_i) actually increases in parallel with the potential dip ($\Delta\phi$), however $\Delta\phi/T_i$ is always higher, following the overall ion confinement. Further, low frequency noise observed in the plasma due to instabilities and parametric decay of high frequency wave affect the ion dynamics by the process of selective ion heating [10, 16]. Due to the limited database of gas mixing experiments; it is very difficult to understand the ion behavior in the plasma and a consistent generalised model still needs to be established.

In present studies, we have recorded the charge state distributions (CSD) of Carbon (C) and Oxygen (O) in pure and Helium (He) mixed (at different %) CO_2 ECR plasma and touched upon various aspects of ion behaviour. Further, the extracted and analysed ion beams from ECR plasma are used for ion-matter interactions studies.

FACILITY DESCRIPTION

The Low Energy Ion Beam Facility (LEIBF) at IUAC, New Delhi, India [17] is a compact accelerator that has been functioning continuously for more than two decades, providing ion beams of energy ranging from tens of keV to a few MeV for diverse materials science and atomic molecular physics experiments. The schematic of the facility is shown in Fig. 1. The LEIBF consists of mainly a 10 GHz all-permanent-magnet ECR ion source, RF power and gas feed systems, efficient ion extraction system and an Einzel lens. All these components along with electronics and vacuum pumps are placed on a high voltage platform (V_{max} = 400 kV). These are powered by using an isolation transformer (10KVA) and controlled by the fibre-optic communication. The ions extracted from the plasma are further accelerated using a general purpose tube (GPT) having electrostatic field gradient. The pre-analysis section of LEIBF consists of electromagnetic lenses, a Faraday cup, a beam profile monitor and a double slit. For the analysis of ion beam in energy and momentum, a large analyser-cum-switching dipole magnet (B_{max} = 1.4 T) is used. For experiments, three beam lines at 75°, 90° and 105° equipped with proper beam line components, are available. The ions extracted from the plasma are transported to experimental chamber at the end of each beam line by focusing and steering those using electromagnetic lenses. All ion source and beam line

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active components are controlled remotely by an in-house-built measurement and control (iMAC) system.

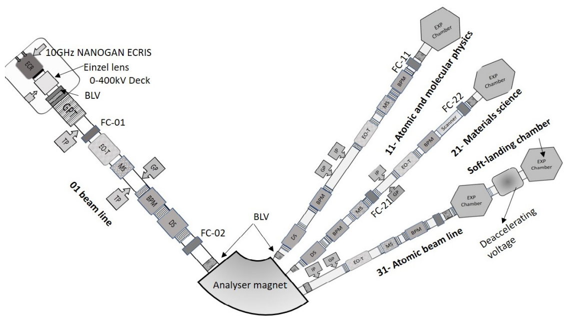

Figure 1: Layout of low energy ion beam facility (LEIBF) at IUAC.

EXPERIMENTAL DETAILS

The ECR plasma was produced by injecting the natural CO_2 gas into the chamber and ion source parameters such as RF power, injector gas pressure, negative DC bias were optimized to the values 2W, 2.11×10^{-5} T, and -72 V, respectively, to stabilize the plasma and also to populate the highest possible charge states of C and O. The ion beam was extracted by applying a 15 kV extraction voltage and then focused by the two gap Einzel lens before passing through the GPT to gain an additional energy of 185 keV/q. For efficient transportation of ions, the electrostatic lenses and magnetic steerers were fine-tuned to maximize the analyzed beam current on the Faraday cup. Further, the double slits at the object and image plane of the analyser magnet were manually adjusted to obtain an undistorted beam envelope, as verified by the BPM. For mixing experiment, the gas pressure of CO_2 was reduced and He gas was injected from the second gas inlet with 50% and 80% of the total throughput. All the source parameters were again optimised to maximize the intensity of highest populated charge state in the plasma. For the comparative study of pure O_2 and CO_2 plasma, the CSD of O in pure O_2 plasma was also recorded.

The 90° beam line in LEIBF is dedicated to the materials science for ion implantation and irradiation experiments. In the course of studying various ECR plasmas, we have studied heavy ion beam induced surface pattering on insulating surfaces. For this purpose, the irradiation of 200 keV Kr ion beam on Si/SiO_2 (300 nm) surface at off-normal angle of 40° has been considered. The total analyzed beam current was 20 µA and the irradiation was done at a fixed ion fluence of 5.0×10^{17} ions/cm^2. The topographic studies of samples were done using atomic force microscope (AFM).

RESULTS AND DISCUSSION

The CSD of O and C in various ECR plasmas; Pure CO_2, 50% He mixed CO_2, 80% He mixed CO_2 and pure O_2 plasma are depicted in Fig.2(a) and Fig.2(b) respectively. The gas mixing effect is very prominent for both C and O in different fractions of mixing. With optimized source parameters, the maximum populated charge state of C and O in pure CO_2 plasma were +5 and +6, respectively and for O, it shifted to +7 with He gas mixing. The spikes appeared at q = 4 (in case of CSD of O) and q = 3 (in case of CSD of C) are due to the overlapping of $^{12}C^{+3}$ and $^{16}O^{+4}$ beams. Further, with the He gas mixing, $^{4}He^{+}$ beam is also measured along with the $^{12}C^{+3}$ and $^{16}O^{+4}$ beams as a contamination. By comparing the CSDs of O in pure O_2 and CO_2 plasmas, it is concluded that the presence of C reduces the intensities of highly charged O ions. The p orbit of C is unfilled and it do not feel much repulsion from the unpaired electrons resulting higher electron affinity. Therefore, the presence of C in the plasma reduces the electron density significantly and hence lower ionization efficiency in such plasmas.

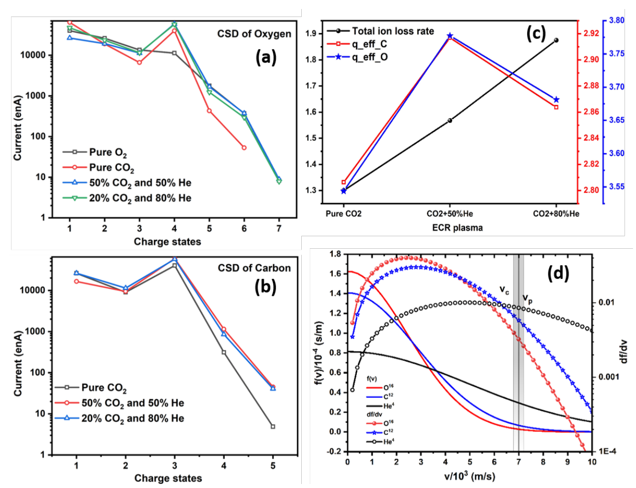

Figure 2: (a) and (b) shows the charge state distribution of O and C in ECR plasma; (c) Total ion loss rate and effective mean charge state of O & C in pure and He mixed CO_2 ECR plasma; (d) Velocity distribution function of ions and its derivative with respect to velocity. Assuming T_i = 1 eV and mixture ratio $\alpha = 1$.

To understand the gas mixing effect, we have to consider all aspects of ion cooling & heating, ion confinement time and electron density. The min-B magnetic field geometry of an ECR source provide high mirror ratio that helps to get the escaping thermal electrons reflected back into the plasma and a high density of electrons in the core gives rise to dip in the plasma potential. The addition of a lighter gas of lower ionisation potential yields extra electrons and so the dip in the plasma potential at the plasma core is further increased. The plasma potential is responsible for the loss of ions by Coulomb scattering and therefore, this so-called lowering of the plasma potential [14] due to gas mixing increases the ion confinement time.

Another explanation of gas mixing effect is given by ion cooling model [18]. According to it, the lighter ions drag energy from the heavier ions by elastic ion-ion collision and escape from the plasma, resulting in more confinement of the heavier ions into the plasma core. Melin et al. [19] derived some sets of formulae to calculate the plasma parameters by measuring the extracted current from the plasma. From

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the fig. 2(c) we can see that the mean charge state of O and C increases with mixing fraction and decreases slightly in the case of 80% mixing. This may be due to a very low neutral atom density of C and O present in the chamber to get ionized.

Further, it has been shown that the input high frequency wave undergoes parametric decay and a low frequency signals/wave observed in the plasma [16]. The energy can be exchanged between ions and this low-frequency waves via Landau damping [20] if ion thermal velocities are comparable to the phase velocity of the wave and for effective damping, the density of ions that take energy from the wave must be large. The velocity distribution function and its derivative for ion species C, O, and He are shown in fig. 2(d). When the phase velocity of the wave exceeds some critical velocity [10], the lighter ions are dominantly heated by the Landau damping for all velocities. This prevents the heating of heavier ions by wave damping in parallel to the reduction in the number of the coolant (lighter ions). However, the overall influence is effective ion cooling, which results in a high intensity of highly charged ions.

The AFM images of pristine and 40° off-normal Kr ion irradiated sample along with the cross-section profile (at the top), and the auto-correlation function A(r) and height-height correlation function H(r) of the pristine and irradiated sample as obtained from the fractal analysis [21] (at the bottom) are shown in Fig. 3. The AFM image of irradiated sample confirms the formation of a well-ordered ripple patterns on the SiO_2 surface and FFT image (shown in in-set) changed from haziness (in pristine sample) to well separated frequency points on either side of the centre (in ion irradiated sample), indicating the shift from disorder to the ordered ripple patterns. The calculated surface parameters from the fractal calculations are shown in Table 1.

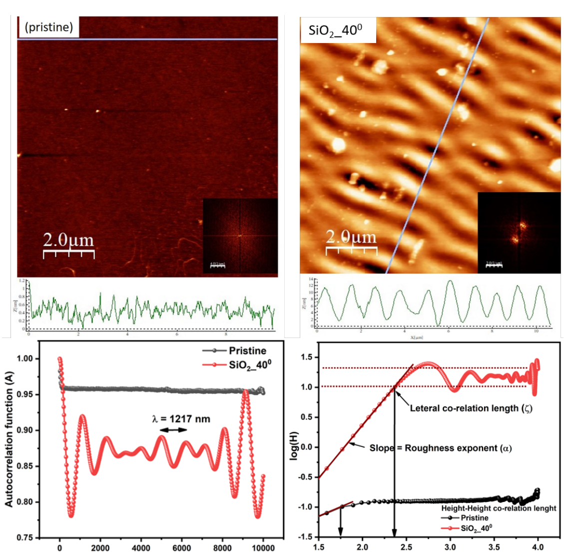

Figure 3: AFM images of pristine and irradiated samples along with cross-sectional view and FFT image (Top) and Auto-correlation function and height-height correlation function (bottom)

Table 1: The Surface Parameters By Fractal Analysis

Parameters	**Pristine SiO_2**	**SiO_2 40°**
Z_{mean} (nm)	1.21	7.03
Interface width (nm)	0.26	2.72
Average roughness (nm)	0.15	2.21
Roughness exponent (α)	0.31	0.88
Correlation length (nm)	54	249
Fractal dimension (D)	2.69	2.11
Wavelength (μm)	—	1.22

The A(r) and H(r) functions are obtained for surface correlation parameters such as roughness exponent (α), lateral correlation length (ζ) and fractal dimension (D), which are independent of the scanning length. The auto-correlation function decays exponentially up to the correlation length after it, the surface is no more correlated and for rippled surface, it shows oscillatory behaviour as evident in present studies. The ripple wavelength, measured from the peak-to-peak separation from oscillatory region in A(r) Vs r plot, was 1.22 μm. Generally, $\alpha = 1$ indicates perfectly smooth surfaces. After 200 keV Kr ion beam irradiation, the roughness exponent increased from 0.31 to 0.88 indicating that the rippled surface has smooth texture.

CONCLUSION

The He gas mixing in CO_2 plasma was found to be very effective with 50% and 80% mixing fractions. The current intensity of the C^{+5} increased almost 10 times, whereas the intensity of the O^{+6} increased almost 4 times. Further, the CSD of O shifted towards a higher charge state (+7 in present case). The comparison of pure CO_2 plasma and O_2 plasma showed that the performance of ion source is reduced in former case due to the fact that C (as an internal mixer) acts as an electron eater in the plasma. The gas mixing results were explained by ion-cooling model and lowering of the plasma potential. Further, the parametric decay of input high frequency wave in the plasma and subsequent ion heating effect by ion-cyclotron resonance and Landau wave damping has also been discussed.

In the course of materials modifications by the bombardment of SiO_2 using a 200 keV Kr ion beam extracted from the ECR plasma, the surface topology as recorded by AFM has been presented. After ion beam irradiation and fractal analysis, a smooth texture of ripples (wavelength in micro-meter) with self-affine properties has been noticed on the surface of SiO_2. The ion beam irradiation/implantation technique is a very effective tool for the controlled surface modification of materials.

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