新たな負イオン研究の応用
Emerging Application Fields of Negative Ion Research

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1. Introduction

Intense beams of negative hydrogen (H^-) ions are required for two research fields: magnetically confined fusion, and high energy proton storage/acceleration in ring accelerators. Sources to produce H^- ions often confine plasma of power density exceeding 10 W/cm^3, while they reduce the temperature of plasma near the beam extractor below 2 eV. Fundamental processes of H^- ion formation in H^- ion sources have been summarized [1], and the development status of the ion source is routinely reported [2]. As the direct application of intense high energy negative ion beam, Si wafer "smart-cut" process has been demonstrated at Japan Atomic Energy Research Institute [3]. However, species other than H^- are necessary for industrial applications of negative ions. Ishikawa [4] had summarized the possible application areas of negative ion beams that can be extracted from his surface production type negative ion source.

Negative ion research includes wide variety of study area in physics and chemistry. Atomic and molecular physics is critically important in understanding formation and destruction processes in the ion source plasma. Plasma surface interaction at the source wall also plays a decisive role in determining overall production efficiency of negative ions. Work function, in particular, determines the negative ionization efficiency for particles reflected, desorbed and sputtered. These pieces of information on fundamental processes can be also applied to other field of science and engineering. Here is reported the candidate application areas where science and technology related to negative ion formation and transport can be utilized.

2. Merits of negative ions

There are two major advantages of using negative ions instead of positive ions. An extra electron in the negative ion affinity level can be easily released as the affinity level if much smaller than ionization potentials of typical atoms and molecules; the electron is loosely bound. The small binding energy makes the cross section for electron stripping in gas molecules for H^- large at energy exceeding 100 keV, which makes the H^- based high energy neutral beam injection system for fusion plasma heating to be efficient enough. Also, negative ions can be neutralized by photon irradiation in the wavelength region of intense lasers.

The other virtue of negative ion is its negative electric charge. When a solid surface is irradiated by an ion beam, it produces secondary electrons. Electrons going out of the surface charges an insulator surface up to positive electrical potential, which will be further enlarged as the positive ions strike the surface. In the case of negative ions irradiate an insulating surface, a single electron emission by an incident negative ion is equivalent to an injection of a neutral particle produced through electron detachment from the incident negative ion. As the result, the surface electrical potential of an insulator under negative ion irradiation is much smaller than that under positive ion irradiation [5].

3. Application to mass analysis

Negative ions have been used as probe beam for SIMS (Secondary Ion Mass Spectrometry) application. Beams of oxygen negative ions are produced by cold cathode duoPlasmatron ion source, and surface ionized sputtered atoms are detected by mass analyzers. On the other hand, the incident beam can produce negative ions at the surface when Cs ions are injected onto the surface as the primary beam. As the surface negative ionization phenomena have been studied for H^- production, optimization of the measurement system based on negative SIMS can be made.

Mass analysis investigations on bio-materials requires incident beam of large cluster ions like C_{60}^+ to scrape off large molecules from sample surface. Positive and negative ion modes are utilized for mass analysis to identify molecular structure [7]. Mapping of lipid species has been successfully accomplished by negative ion mode of MALDI-ion

mobility imaging system [8]. Fragmentation analyses of large molecules are also done by detecting negative ions [9]. In these applications, understanding of the formation processes of negative ions is important in identifying the molecular structure of the sample.

Realization of a negative ion beam of C_{60} is a challenging research topic for a negative ion physicist. The electron affinity of C_{60} should be as high as 2.68 eV [10], and efficient production of negative ion of C_{60} is expected. As the parent molecule is fragile, low temperature plasma suitable for electron volume process may produce negative C_{60} ions with an enough reaction rate.

4. Application in material science

Plasma based material synthesis has achieved a significant progress. Atomic and molecular process in a plasma coupled to target surface science determine the material synthesis capability of the production system. The behavior of negative oxygen ions in a plasma is found important in preparation of ZnO film [11]. Introduction of negative ion species into a plasma will yield another tuning knob to control reactions in the plasma. Knowledge obtained in the negative ion research can be applicable to develop a better material production system.

Plasma surface treatment has become popular, and functional surfaces are realized by plasma exposures. For example, adhesion between polyimide and metal is improved by irradiating the surface of polyimide film with an oxygen plasma [12]. The negative ions in plasma determines the sheath potential, and the surface erosion due to sputtering and chemical etching. Methods to properly control spatial distributions of plasma parameters are readily applicable to realize desired a flux of reactive ion species.

5. Space charge neutralization

Low energy large current ion beams easily diverge due to a space charge effect. Ions with electrical charge of the opposite sign of the beam ions will neutralize the space charge, and mitigate the ion beam to diverge. Space charge arising from concentration of positive ions can be mitigated by electrons, but high mobility of electrons causes oscillations to make the plasma unstable. Negative ions may be more suitable to reduce space charge due to a positive ion beam.

The problem of "charge-up" is also serious in electric space propulsion. An electron gun neutralizer is combined with an ion-engine for a space satellite to avoid charge up of the space craft, but part of the extracted ions can inside of the neutralizer to damage by ion bombardment. The positive ion negative ion alternate extraction system removes additional component to electrically neutralize the space craft. Characteristics of an ion-ion plasma have been extensively studied in H^- ion source for fusion experiments [14]. Efficient beam extraction from ion-ion plasma of future ion engine can be studied from H^- ion source physics.

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