| | |
|---|---|
| | ふじわら　ゆきお |
| 氏　　　　名 | 藤　原　　幸　雄 |
| 授　与　学　位 | 博士（工学） |
| 学位授与年月日 | 平成15年3月24日 |
| 学位授与の根拠法規 | 学位規則第4条第1項 |
| 研究科，専攻の名称 | 東北大学大学院工学研究科（博士課程）機械知能工学専攻 |
| 学位論文題目 | 固体イオニクスおよび放電プラズマを用いた負イオンビーム源に関する研究 |
| 指　導　教　官 | 東北大学教授　水崎　純一郎 |
| 論文審査委員 | 主査　東北大学教授　水崎純一郎　東北大学教授　湯上　浩雄<br>東北大学教授　寒川　誠二<br>東北大学助教授　二唐　裕 |

# 論文内容要旨

The investigations compiled in this thesis are aimed at solving problems for the development of negative-ion beam sources. The following two main topics were examined: (i) a new method for producing negative ions with solid state ionic devises (Chapter 2) and (ii) problems in the development of negative-ion beam sources capable of producing high-current and high-energy negative-ion beams with plasma devices (Chapter 3, 4, 5 and 6).

In Chapter 2, the authors proposed a simple method using solid oxide ionic conductors named solid oxide ion source (SOIS). Conventional methods using plasma devices are complicated and expensive, whereas the SOIS is simpler and cheaper. To demonstrate the SOIS, emission characteristics of oxygen negative ions from surfaces of yttria-stabilized zirconia (YSZ) ceramics were investigated using a quadrupole mass spectrometer capable of detecting negative ions at elevated temperatures.

Experimental results demonstrated that oxygen negative ions, $O^-$, are emitted into a vacuum selectively from YSZ surfaces at elevated temperature. Hence, the concept of SOIS has been verified in principle. It was found that the number of emitted $O^-$ ions increases with temperature of YSZ. Thus, it is effective to raise temperature so as to promote the emission of $O^-$ ions. Experimental results in continuous operation showed that emission rate of $O^-$ ions decreased with the passage of time. However, it was found that intervals temporarily recover the emission rate. Thus, short-pulse operations will be suitable for use in terms of applications.

On the basis of the experimental results, the authors have proposed a model for explaining the emission mechanism of $O^-$ ions from solid oxide ionic conductors. The model is based on three key processes occurring on the surface of solid oxide ionic conductors: (a) formation of oxygen negative ions on the surface by electron capture of oxygen atoms provided by the migration of oxide ions across the solid oxide ionic conductors, (b) accumulation of oxygen negative ions on the surface, and (c) emission of $O^-$ ions that are present on the surface when an electric field is applied. Using the model, the experimental data were analyzed; it was shown that the rate determining step of the emission mechanism of $O^-$ ions would be the formation process of $O^-$ ions on the emission surface. It was shown that the dominant emission process would be the emission from chemisorption sites on the surface rather than the direct emission from anion sites in the solid oxides at relatively lower temperatures like the present experiment. It was also shown that the transient response of $O^-$ emission would be explained by considering the variation in fractional coverage of chemisorbed oxygen on an emission surface.

To control the emission rate of $O^-$ ions, the authors studied the effect of electrochemical polarization between an air electrode and a platinum-coated emission surface. Experimental results showed that electrochemical oxygen pumping slightly affects the emission rate of $O^-$ ions. In the case of negative (i.e. cathodic) polarization, the emission rate was increased. On the other hand, it is decreased in the case of positive (i.e. anodic) polarization. Such results will be due to the variation in work function on the YSZ surface.

The authors think that the variation in work function will affect the formation process of oxygen negative species on an emission surface, so that surface density of oxygen negative species on the emission surface will be varied by electrochemical polarization, leading to the variation in the emission rate of $O^-$ ions. In other words, the decrease in the work function will enhance the formation of oxygen negative species, resulting in the increase in the emission rate. That is, it will be effective to reduce the work function of materials on the surface so as to increase emission current.

In conclusion, the authors showed that it is possible to produce negative ions by a simple and easy method with solid state ionic devices. Since the method is much simpler and easier than conventional methods using plasma devices, the authors expect that the method with solid state ionic devices will have great potential, opening up new fields in materials science and technology as well as solid state ionics.

In Chapter 3, optimization of the surface production process of negative ions was examined in the case of cesium-seeded volume production negative ion source. In general, the effect of the surface production is several times higher than that of the volume production. Hence, to obtain high-current negative-ion beams, the surface production process must be optimized continuously over a wide extraction area. To optimize the surface production, it is required to maintain cesium coverage at optimum value, about one-half monolayer, over a wide extraction area in continuous operation. The cesium coverage is determined by evaporation-condensation balance on a substrate. Eventually, it is required to control substrate temperature so as to produce negative ions efficiently via the surface production process.

To control substrate temperature continuously at optimum for surface production process over a wide extraction area, a frame-cooled plasma electrode was designed in view of temperature and stress distributions using three-dimensional numerical simulations. As a material of the plasma electrode, copper-chrome-zirconium (CuCrZr) was examined, since it has high mechanical strength as well as high thermal conductivity. The numerical simulations indicated that the plasma electrode would be kept at about 300 °C, which is optimum temperature for negative-ion production. They also indicated that thermal stress in the plasma electrode would be less than yield stress.

To demonstrate it, a frame-cooled plasma electrode was fabricated and tested. Experimental results showed that its surface temperature is continuously kept at optimum over a wide extraction area. Thus, it was demonstrated that the frame-cooled plasma electrode is applicable to long pulse or continuous operations, meeting the temperature requirement for the surface production process; in other words, optimization of the surface production process can be achieved.

In Chapter 4, the influence of space chare between beamlets on beam optics was studied. In view of applications, beam optics is one of the most important properties of ion beams. Especially, in high-power ion beam sources, acceleration of beams in good optics is required to prevent high-power beams from damaging components of beam sources themselves.

To clarify the influence of space charge between beamlets on beam optics, beamlet-beamlet interaction in an acceleration region was studied at the beam energy ranging from 86 keV to 178 keV. Experimental results showed that the deflection angle of beamlets at the edge of a beam was about 3 mrad larger than that at the center of the beam. The deflection angle was independent of beam energy at the same perveance. It was also found that repulsive force due to the beamlet-beamlet interaction was inversely proportional to the square of distance approximately. Thus, the influence of the beamlet-beamlet interaction was found to be not negligible. However, from a beam trajectory calculation, shaping of an electrode was confirmed to be effective to compensate the influence of the beamlet-beamlet interaction. In other words, it is possible to compensate the influence of the space charge on beam optics, although the influence is not negligible.

In Chapter 5, thermo-mechanical reliability of an acceleration electrode in a negative-ion beam source was examined. Unlike positive-ion beam sources, electrons are also accelerated with negative ions in negative-ion beam sources. Accelerated electrons will result in significant heat load on acceleration electrodes. Thermal deformation of the acceleration electrodes will cause beam distortion, since thermo-mechanical reliability of acceleration electrodes is one of the most important issues in high-power negative-ion beam sources. As an example, an acceleration electrode for producing 40 MW ion beams was examined using numerical simulation. Numerical simulation showed that maximum aperture-axis displacement of the acceleration electrode due to thermal expansion would be about 0.7 mm for the heat loading of 1.5 MW. From the thin lens theory of beam optics, beamlet deflection angle by the aperture-axis displacement was estimated to be about 2 mrad. Numerical simulation also indicated that no melting on the acceleration electrode would occur for a heat loading of 1.5 MW, nevertheless, local plastic deformation would happen. To avoid the plastic deformation, it is necessary to reduce the heat loading onto the acceleration electrode to less than 1 MW.

Further, the authors showed that a new method using two types of computational models, the one-half model and the local model, was useful to evaluate thermo-mechanical characteristics of a large acceleration electrode. The authors expect that the method will also be helpful in the evaluation of the thermo-mechanical reliability of acceleration electrodes of other negative-ion beam sources.

In Chapter 6, the influence of radiation on insulation gas around negative-ion beam sources was studied. In high-energy ion beam sources, insulation gas is used for high-voltage insulation. In the case of negative-ion beam sources, electrons are also accelerated with negative ions. Since accelerated electrons generate undesirable X-rays, insulation gas around beam sources is ionized by the X-rays. Hence, in negative-ion beam sources, ionization current through the insulation gas will be one of serious problems, resulting in heat load of the insulation gas as well as loss of electric power. In addition to the X-rays, in the case of negative-ion beam sources for nuclear fusion research, insulation gas will be irradiated with neutrons and gamma rays generated by nuclear fusion reactions. Thus, the influence of radiation on the insulation gas is one of the most urgent issues in the development of high-energy negative-ion beam sources for fusion research.

To clarify the influence of radiation on insulation gas, ionization currents and voltage-holding characteristics of gases were studied using the $^{60}$Co gamma rays. The experimental results showed that saturation current increases linearly with gap length between parallel electrodes, gas pressure, and absorbed dose rate. The saturation current also increased with molecular weight. In particular, in the case of molecular weigh less than about 50, the saturation current was proportional to the molecular weight. Degradation of voltage-holding capability during irradiation was about 10 %; the degree of the degradation did not depend on absorbed dose rate. Further, it was found that a small quantity of $SF_6$ gas mixed with air has lower ionization current and higher voltage-holding capability; mixture of a little $SF_6$ gas will be effective from the viewpoint of suppressing ionization current.

On the basis of experimental results, an experimental formula for estimating saturation current was obtained. From the results, it was found that ionization current would not be negligible in high radiation conditions. In such high radiation conditions, other insulating methods such as vacuum insulation will be necessary instead of gas insulation.

# 論文審査結果の要旨

イオンビームは材料科学技術，高エネルギー物理，核融合などの様々な分野で広く利用されている．正イオンビームを利用したものが一般的であるが，最近ではその制御のしやすさと照射体のチャージアップによる損傷の危険が少ないことから負イオンビームに高い関心が集まっている．本研究は負イオンの発生から大きな流束と高いエネルギーを持つ負イオンビーム取り出しに至る負イオンビーム源全般の高機能化を目指して，そこにある主要課題に解を与えることを目的としている．第2章ではイオン導電性固体を負イオンビーム源として用いることを試みた学術的研究の成果を，また第3章から6章では日本原子力研究所で計画中の国際熱核融合実験炉における高流束高エネルギー負イオンビームの高精度制御技術開発に関する研究成果をまとめたものであり，全編7章よりなる．

第1章は序論であり，本研究の背景と目的を述べている．

第2章では，イオン導電性固体に高電圧をかければイオンが固体から放出されて，イオンビーム源になるのではないかという着想に基づいて進められた酸素負イオンビーム源に関する研究成果を述べている．先ず，酸素イオン導電体である安定化ジルコニア管の内側に空気を導入，外側は高真空チャンバー内に曝し高温保持した後，チャンバー内にジルコニア管と離して設けたイオン引き出し電極とジルコニア管内側に接した電極との間に電圧を与え，チャンバー内の他の電極に集まる電流やガス圧変化などから酸素イオンビーム発生を確認している．また，それが1価の酸素負イオンビームであることを質量分析計により確認している．更に，同時に出てくる電子ビームとイオンビームの間に減衰時定数の違いがあることを見出し，電圧を与えた直後には電子ビームが強く出ること，その後イオンビームが支配的になることなどを明らかにしている．新しい負イオンビーム源として注目されるとともに，イオン導電体を扱う固体イオニクスの研究分野における重要な発見である．

第 3 章は従来から用いられているプラズマ生成による重水素負イオンビーム発生装置の高効率化についての研究成果を述べている．負イオン発生の場として多数設けられた発生装置内の壁温度を場所に依らず300℃程度に保つことが必要であるため，外壁との間の熱絶縁を達成する独自の壁構造をシミュレーションから導きだし，実験により検証している．

第4章はイオンビーム間の相互作用によるビーム束の広がりを押さえ，収束性をよくするための研究の成果であり，引き出し電極の肉厚をビーム束の中央に向かう側を薄く，外周部に向かう側を厚く制御することで並行ビーム束が得られることを実験と理論計算から明らかにしている．

第5章では，イオンビーム加速電極の熱による変形の程度と，それがビーム束の収束性にもたらす影響について，核融合実験炉の高エネルギーイオンビームの加速電極を対象として計算モデルを構築しシミュレーションによって評価している．考案した二通りのモデルが整合性のある計算結果を与えること，加熱による電極変形の影響が許容される限度内であることなどを明らかにしている．

第6章では，負イオンビームと同時に発生する高エネルギー電子ビームがビーム源周りの絶縁ガスに与える影響，特にガスのイオン化による二次X線の発生について検討している．その結果フッ化硫黄ガスを微量空気に混入させることがイオン化電流の阻止に有効であるという結論に達している．第3章から第6章で導かれた成果は何れも精度の高い高流束・高エネルギー負イオンビーム源の構築に極めて重要な知見である．

第7章は結論である．

以上要するに本論文は，負イオンビームの新しい発生源の提案と，高流束・高エネルギー負イオンビーム源の構築に必要な要素技術課題のそれぞれに解を提起したもので，固体イオニクス科学，イオン工学，機械知能工学の発展に寄与するところが少なくない．

よって，本論文は博士(工学)の学位論文として合格と認める．