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論文内容の要旨

It is well known that the interactions of energetic particles with solid surfaces lead to the emission of particles such as electrons and target atoms from the target surface. This is usually referred to as the secondary particle emissions. One of the fundamental observations of this phenomenon is the measurement of the secondary particle emission yield, $\gamma$, defined as the average number of particles emitted per the incoming particle. There are a lot of experimental as well as theoretical studies on the secondary electron emission yields induced by ion impact on the *metal surfaces*. Therefore, the relevant mechanisms have been understood reasonably well. However, investigations on the secondary ion emission yields have still been limited.

Furthermore, only a few attempts have been made so far in understanding phenomena under ion impact on the *non-metallic surfaces* though alkali-halides have been investigated in some details. Therefore, we do not have sufficient understanding in the interaction mechanisms between ions and non-metallic surfaces.

The purpose of the present study is to reveal any difference in the interactions of ions with metal and non-metallic surfaces. Such studies are of great importance not only in basic physics but also in applied fields such as very-large-scale-integrated-circuits (VLSI) technology, fusion plasmas, surface analysis etc.

In the present study, the secondary electron emission yields, $\gamma^-$, and the secondary positive ion emission yields, $\gamma^+$, from some non-metallic surfaces induced by low energy ion (0.3～100 keV $H^+$, 2.5 keV $H_2^+$ and 2.5～150 keV $Ar^+$) impact have been measured using a cylindrical double-wall cup under an ultra high vacuum chamber (～$10^{-11}$ Torr) pumped down with the combination of a turbo molecular pump, an ion pump and a titanium sublimation pump with a liquid nitrogen trap. In order to clean the target surfaces they were sputtered with argon ions and also heated with a ceramic heater placed behind the target. An Auger electron spectrometer has been used in order to check the surface cleanness.

It has been found that the observed $\gamma^-$ from the non-metallic surfaces is proportional to the electronic stopping power over the collision energy range investigated. It is noted that similar relations are well known in metal targets. However, the proportional coefficients in $\gamma^-$ are 2-3 times larger than those for metal targets. These results also agree with tendencies for oxygen-covered metal surfaces observed in the present experiment which show that $\gamma^-$ increases as the oxygen coverage increases. We have also observed, for the first time, an interesting phenomenon where the observed $\gamma^-$ strongly depends on the incident ion beam flux and becomes zero above a critical ion flux for $SrCeO_3$ target.

Similarly, we have found that the observed $\gamma^+$, which has been found to be independent of the incident ion flux investigated, is larger than the results calculated with the TRIM code. It has been found from TRIM code calculations, however, that a significant part of the observed $\gamma^+$ in proton and hydrogen molecular ion impact are due to the secondary electrons emitted from the wall of the inner cup under impact of the neutral primary particles backscattered from the target surfaces. Nevertheless, the observed $\gamma^+$ from non-metallic targets under argon ion impact is far large, compared with the calculated results. Then it has been found that $\gamma^+$ induced by argon ion impact on $SrCeO_3$ is proportional not to the nuclear stopping power, but to the electronic stopping power. This result shows that a greater part of these secondary ions are not emitted by physical sputtering. The observed $\gamma^+$ in 2.5 keV argon ion impact seems to be in reasonable agreement with that extrapolated from the data available which is believed to be due to the Coulomb explosion on the non-metallic surfaces.

Furthermore, in order to identify the mass and energy of the secondary positive ions emitted from targets, two different techniques have been used: One was a collector method using graphite and beryllium sheets which were analyzed with Rutherford backscattering technique using 1.8 MeV helium ions. Another was the mass and energy analysis with a quadrupole mass spectrometer attached with four meshes, to which the retarding voltage was applied for kinetic energy selection.

Both experiments confirm that target elements are emitted as ions (as well as neutrals) by the incident ion impact. Furthermore, the second experiment shows that these emitted ions have large kinetic energy, comparable to the incident ion energy. Such large kinetic energy can be qualitatively understood to be provided probably by the electrostatic potential caused by local charge-accumulation of the incident ions on the non-metallic surfaces due to their high resistivities. This phenomenon can also explain how the observed $\gamma^-$ depends on the incident ion beam fluxes because some fractions of the electrons produced in the target are not able to overcome the Coulomb barrier generated by accumulation of the incident ion charge and can not be liberated into vacuum.

It is concluded from the present work that the key mechanisms responsible in the secondary particle emissions from the non-metallic surfaces are very different from those in metal targets induced by the energetic ion impact.

## 論文の審査結果の要旨

本研究論文は非金属表面への低エネルギーイオン衝突による粒子放出に関する実験的研究をまとめたものである。

金属表面にイオンが入射した際の2次電子放出に関する研究は、 実験的にも、理論的にもよく行われ、その機構はよく理解されている。一方、非金属表面にイオンが入射した際の2次粒子放出現象を研究したものは少なく、アルカリ結晶を標的とした研究がいくつかあるに過ぎない。

このような現状に鑑み、イオンと固体表面の相互作用において金属と非金属とでの違いを調べることを目的とした。これは、基本的なビーム・固体相互作用の物理現象の理解ばかりでなく、核融合炉における内壁とプラズマとの相互作用、超大規模集積回路技術、表面解析技術など応用分野においても非常に重要なものである。

本研究では、数種類の非金属標的を用いて、低エネルギーイオン（300 eV-100 keV の $H^+$, $H_2^+$, $Ar^+$）の入射によって固体表面から放出される全2次負電荷粒子放出率$\gamma^-$及び全2次正電荷粒子放出率$\gamma^+$を測定している。実験での衝突エネルギー領域では、$\gamma^-$は金属の場合と同様に電子阻止能に比例することを観測した。しかし、$\gamma^-$の阻止能に対する比例定数は金属の場合より2、3倍大きいことが分かった。また、入射イオンビームの電流強度を増加していくと、ある強度以上で$\gamma^-$が0になるという特徴的な現象を初めて見いだした。

一方、$\gamma^+$はシミュレーションおよび既存の関連データの解析から得られる値よりも大きいことが示されたが、特に、アルゴンイオンに対する$\gamma^+$は非金属表面におけるクーロン爆発によるイオン放出が最も効いていると評価された。また、グラファイトとベリリウムを用いた捕集方法で、放出されたイオン種を調べた結果、標的を構成する元素がイオンとして放出されていることを確認した。また、減速法で放出イオンの運動エネルギーを測定した結果、放出イオンは、800eVの入射イオンに対して数百eVの大きな運動エネルギーを持つことが分かった。これは、電荷をもつ入射イオンと固体表面との相互作用によって生じる電荷蓄積により、非金属表面で局所的に大きな静電ポテンシャルが生じたためであると理解される。これは、また、入射イオンがある強度以上になると、$\gamma^-$が0になるという特徴的な現象も、局所的に蓄積された電荷によって生じたある静電ポテンシャル以上で2次電子が放出されなくなったとして説明できる。

以上、金属表面の場合との明確な違いを見い出すなど、興味深い実験結果を得ており、研究の独創性も認められる。

よって、本審査委員会は、新しい知見を得た成果と当該分野への貢献の程度から判断して、本論文が博士学位論文として十分の資格があると認めた。