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学 位 論 文 題 目	Studies of Inductively Coupled Chlorine Plasma for Semiconductor Etching Processes Using Time-resolved Laser Spectroscopy (時間分解レーザー分光法を用いた半導体エッチングプロセスのための誘導結合塩素プラズマの研究)
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論文内容要旨

Chapter 1 Introduction

Reactive gas plasmas are indispensable for semiconductor etching processes. As the required rule size has become smaller than $0.1 \mu\text{m}$, several problems such as the degradation of the MOS devices due to the charging damage and local side etching due to the local charge-up, which is called “notch”, have become serious. For those problems, time-modulated plasma etching technique was proposed. The plasma discharge was cut off periodically in this etching technique. The ion density was kept high while the electron temperature was lowered. In addition, a number of negative ions were produced in the discharge-off period. It was considered that the alternative impinging of the positive and negative ions could neutralize the charge accumulated on the wafer. As a result, charging damage free and notch free etching characteristics were obtained.

Cl_2 gas plasma has been widely used for the silicon etching processes. The etching reactions were enhanced by the ion bombardment to the surface. For the superior etching, it is important to clarify the etching reactions in bulk plasma and on wafer. The major problems in Cl_2 plasma etching were as follows. The densities and temperatures of individual ions such as Cl_2^+ , Cl^+ and Cl^- , which were responsible for superior etching, were not investigated in the bulk time-modulated plasma. The amounts of chlorine ions change depending on the time-modulation as well as the conventional plasma parameters such as power, gas pressure bias voltage etc. Therefore, it is essential to measure those ions in the time-resolved experiments. The measurements of ion density in the bulk plasma are indispensable to discuss the plasma time-modulation frequency for effective etching. The ion temperature affects the ion impinging energy on the wafer. Moreover, the fluxes and energies of those ions impinging on the wafer surface have also been unclear although they affect the etching characteristics directly.

In this dissertation, the ions have been measured in the inductively coupled Cl_2 plasma using time-resolved laser spectroscopy. In the bulk Cl_2 plasma, the densities of Cl^+ , Cl_2^+ and Cl^- ions were measured under the same experimental conditions. In addition, combining the laser spectroscopy technique with a micro sensor fabricated with semiconductor microfabrication technique, ion fluxes were measured on wafer with newly developed on-wafer monitor probes.

Chapter 2 Development of metastable atomic chlorine ions

Plasma source and a time-resolved laser spectroscopy system were developed. Plasma was generated by inductively coupling method. Ion species were measured using laser-induced fluorescence technique. As for the time-resolved laser spectroscopy system, The time resolution of the developed laser spectroscopy system was 5 ns. The linewidth of the laser was 0.02 cm^{-1} , which was much smaller than Doppler profile. Therefore, the developed system was suitable for ion measurements in the etching plasma. By shifting the laser wavelength to the center of the spectrum, the ion density was measured. The ion temperature was evaluated from the Doppler profiles measured by shifting the laser wavelength.

Chapter 3 Measurement of metastable chlorine ions

Relative density and temperature of metastable chlorine ions (Cl^{+*}) in the time-modulated plasma were measured for the first time with time-resolved laser-induced fluorescence technique. Figure 1 shows Cl^{+*} density as a function of time. In the discharge-off period, Cl^{+*} density was 50% of the maximum density. The Cl^{+*} density decreased with the time constants of about $10 \mu\text{s}$ in the discharge-off period.

Therefore, the 50 kHz plasma time-modulation frequency (50% duty ratio) was preferable to maintain high Cl^{+*} density in this plasma etching system. The diffusion coefficient obtained experimentally agreed well with that of theoretical value. Therefore, the Cl^{+*} density decay was explained by the diffusion to the chamber wall.

The Cl^{+*} temperatures were measured as a function of time. The temperature decreased from 4000 K to 3000 K in the discharge-off period. It was considered that Cl^{+*} temperatures were decreased by collision with other plasma species. In the discharge-off period, positive ion diffusion was slow due to the ambipolar diffusion with the negative ions. In addition, since the plasma uniformity was improved, the gradient of the electric field which accelerate the ion velocity become small.

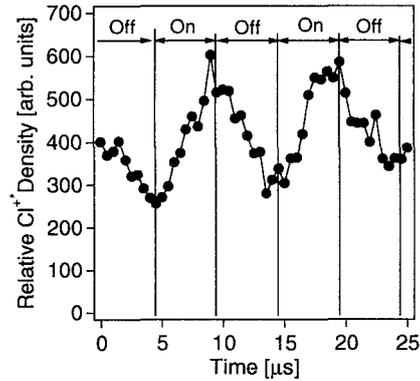


Fig.1 : Cl^{+*} density as a function of time. RF power and gas pressure are 700 W and 2 mTorr. Time-modulation frequency is 100 kHz.

Chapter 4 Measurement of molecular chlorine ions

Relative density and temperature of Cl_2^+ in the time-modulated plasma were measured for the first time with the time-resolved laser-induced fluorescence technique. The Cl_2^+ measurements were carried out under the similar conditions to those in Chapter 3. The decay time constants of the Cl_2^+ density ranged from a few tens of microseconds to a few hundreds of microseconds. The lifetime of the Cl_2^+ ions was longer than that of the Cl^+ ions. The Cl_2^+ density in the discharge off period was discussed considering the rate equations. The Cl_2^+ density was dependent on the ionization from Cl_2 ground state, the recombination with Cl^- ions, the charge-transfer between Cl^+ and Cl_2 , and the Cl_2^+ diffusion to the wall. Among them, the diffusion rate was large. The long life time was explained by the ambipolar diffusion. In addition, Cl_2^+ temperatures were measured. The Cl_2^+ temperature was in the range from 2000 K to 3500 K.

Chapter 5 Measurement of negative chlorine ions

The Cl^- density was measured as a function of time with photodetachment method. The Cl^- density was low in the discharge-on period and high in the discharge-off period. Cl^- ions were generated by the dissociative electron attachment. Since high energy electrons which detached electrons from Cl^- ions still persisted in the beginning of the discharge-off period, the Cl^- density increases slowly. The Cl^- density became maximum around 15 μs from the discharge-off time and then decreased. From the measured results, the plasma time-modulation frequency lower than 30 kHz (50% duty ratio) was suitable for generating high Cl^- density in this plasma etching system.

Chapter 6 Positive and negative ions in bulk plasma

The measured densities of positive ions in the bulk time-modulated plasma were compared with those in cw plasma. The measured results in the LIF experiments were calibrated to obtain the absolute ion densities by using the results of the Langmuir probe measurements. Although the Cl^+ ions were dominant in cw plasma, the Cl_2^+ density was comparable to the Cl^+ density in the time-modulated plasma under the measured conditions. The time-modulation of the plasma discharge lowered the dissociation of feedstock Cl_2 gas under the measured conditions.

In addition, time-variation of Cl_2^+ , Cl^+ and Cl^- densities were discussed. The time-variation of the Cl_2^+ density was smaller than the time-variations of the Cl^+ and Cl^- densities.

Chapter 7 Wafer probe

Ion measurements were carried out in the vicinity of the wafer using newly developed on-wafer monitors, "wafer probe". The wafer probe for positive ion measurement were fabricated. Chromium electrodes were evaporated on the silicon wafer and contact holes were patterned by resist on them. The contact hole size was 1 μm . The probe was set on the etching stage. Positive ions were measured as a function of rf power in the cw plasma and time-modulated plasma. Positive ion densities were increased with increasing rf power.

As for Cl^- ions, they were measured on wafer for the first time using the newly developed wafer probe and photodetachment method. Figure 2 shows a principle of the Cl^- detection in the vicinity of the wafer. Chromium electrode and contact holes were fabricated on a quartz substrate. The Cl^- ions in the hole were irradiated by the laser light from the back side of the on-wafer monitor. The photodetached electrons were detected by the electrode fabricated in the bottom of the side wall. With increasing the time from discharge-off time, the Cl^- ions became detectable with the wafer probe around $20 \mu\text{s}$. From the fact that the Cl^- ions were detected on the wafer, the Cl^- ions impinged on the wafer due to the collapse of the positive ion sheath. The Cl^- densities were also increased with the increase of rf power.

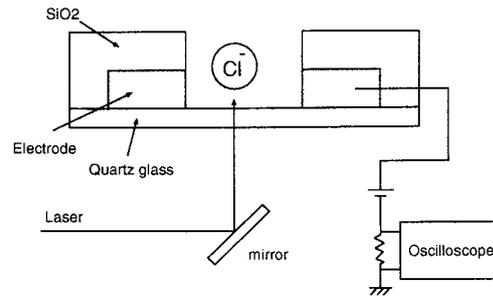


Fig.2 : Principle of Cl^- detection on wafer.

Chapter 8 Comparison of bulk with on-wafer measurements

The ion densities measured in the bulk plasma were compared with those in the vicinity of the wafer surface. The transportations of ions were discussed. In positive ion measurements, the measured ion (Cl^+ , Cl_2^+) densities in bulk and on-wafer showed similar tendencies on rf power.

In the discharge-off period, the Cl^- density measured in the bulk plasma was compared with that measured in the vicinity of the wafer. The Cl^- ions detected with the wafer probe began to increase from around $20 \mu\text{s}$ after the discharge was turned off while the Cl^- densities in the bulk plasma becomes maximums around $15 \mu\text{s}$. It took longer time for the Cl^- ions to impinge on the wafer. The Cl^- density was also measured as a function of rf power. The Cl^- density increased with increasing rf power in both bulk and on-wafer regions.

Chapter 9 Summary

The conclusion of this dissertation was given.

審査結果の要旨

近年、半導体プロセスのイオンエッチング技術に導入された時間変調法はエッチング形状の改善に有効である。著者は時間変調塩素プラズマにおいてレーザ誘起蛍光法を導入し、エッチング機構の解明に不可欠な正負イオン密度を測定した。また、オン-ウェハ計測法を用いてプラズマからウェハへ流入する塩素イオンの挙動を明らかにした。本論文は、この研究成果についてまとめたもので、全文9章よりなる。

第1章は序論であり、本研究の背景及び目的を述べている。

第2章では、本研究で使用するプラズマエッチング装置及び時間分解レーザ誘起蛍光測定装置の開発に関して記述している。

第3章では、時間変調プラズマ中の準安定塩素原子イオン密度および温度を初めて測定した結果について述べている。放電オフ時にも放電オン時の50%の準安定塩素原子イオン密度が検出された。またドップラー幅の測定よりゆるやかな温度変化を観測した。これらの結果は塩素原子正イオンの挙動を理解する上で欠かせない成果である。

第4章では、時間変調プラズマ中の塩素分子イオン密度を初めて測定した結果について述べている。分子イオンの減衰時定数を得た。これらはエッチングにおける分子イオンの効果を考察する上で有用な成果である。

第5章では、プローブ測定とレーザ光脱離法を組み合わせ、塩素負イオンを測定した結果について述べている。正イオンと異なり、放電オフ時に密度が増加し最大値を取る。放電オフ時の特異なイオンの生成消滅機構を理解する上で重要な成果である。

第6章では、連続プラズマにおいて塩素正負イオンを測定し、時間変調プラズマと比較した結果について述べている。イオンの生成に対する時間変調の効果を明らかにする上で欠かせない成果である。

第7章では、ウェハ表面へのイオンの流入をオン-ウェハセンサにより測定した結果について述べている。ウェハへの塩素負イオンの流入に時間遅れが生じていることが明らかにされた。

第8章では、プラズマ中とウェハ上での塩素イオンの測定結果を比較し、それらの相関より時間変調プラズマの特性を明らかにした。

第9章は結論である。

以上要するに本論文は、レーザ分光法を用いて時間変調塩素プラズマ中およびウェハ上の塩素正負イオンの挙動を総合的に明らかにすることに成功したものであり、精密加工学および計測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。