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論 文 内 容 要 旨

Particle contamination in plasma etching equipment is one of the most serious problems in manufacture of large-scale integrated circuits (LSI). For example, particles often cause short circuits between the gate electrode and the source/drain in interconnecting process and lowered production yield of LSI. Overall equipment efficiency (OEE) also decreases because equipment must be stopped for maintenance and cleaning of the chambers. The development of particle-free processes and equipment in mass production of LSI requires studies on real contaminant particles in an actual manufacturing environment [1, 2]. During plasma etching process, the etching reaction products adhere to the inner walls of the process chamber, and gradually form films as wafers are processed. A few particles are constantly generated by flaking of the deposited films caused by electric field stress that acts at the boundary between the insulating inner wall and the film during plasma processing [3]. The electric field is formed between the inner wall surface at the floating potential and the chamber at the ground potential. On the other hand, many flaked particles are sometimes generated unpredictably during etching processes and result in a number of defective LSI devices. The particles seriously lower the production yield and OEE. In this study, to elucidate such an unpredictable particle generation, the mechanism is investigated under mass production condition and the practical detection method is developed.

The experimental apparatus used in this study is the mass production reactive ion etching (RIE) equipment which features a capacitive rf (13.56 MHz) discharge with a parallel plane geometry, as shown in Fig. 1. A wafer with a diameter of 200 mm is chucked on the powered electrode by an electrostatic chuck (ESC) with backside cooling using helium (He) gas. The etching process sequence and equipment parameters are the same as those used in actual manufacturing facilities. This study uses a tungsten etch back process that often causes significant particle contamination. The in situ particle monitoring system, a viewing port style plasma probe (VP-Probe), and an ESC wafer stage with a built-in acoustic emission (AE) sensor are employed in this study [4]. In the particle monitoring system, a sheet-shaped laser beam is introduced in a plane parallel to the wafer in the processing chamber at a distance of 4 mm from the ground electrode. The light scattered by particles crossing the beam is measured using an image-intensified charge-coupled device (CCD) camera. The system can measure the generation of particles together with the status signals of the RIE equipment such as rf power. The VP-Probe can detect a transient change in the floating potential formed on the inner surface of the viewing port [5]. Because the deposited film formed on the inner wall is also at the floating potential and electric field stress is proportional to the square of the electric field generated by the potential [6], the probe can also detect the change in stress acting on the film. The AE sensor in the ESC wafer stage can detect unusual wafer movement [7]. The signals of VP-Probe and AE sensor are simultaneously monitored along with the status signals of the RIE equipment.

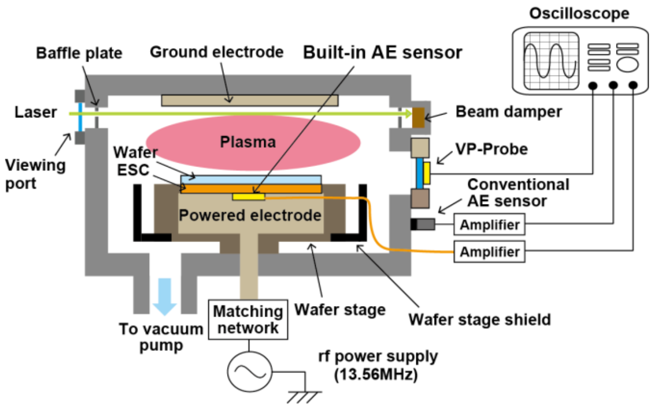

Fig. 1 Experimental setup

Particles appear after the etching of several hundred wafers. Their origin is, therefore, the flaking of etching reaction products from the film deposited on the ground electrode. Figure 2(a) shows the relationship between the number of particles and the operation of the etching equipment. In the etching process, at 53.3 s, the He flow rate increases unusually during the course of cooling due to the wafer movement and a large number of particles are observed at the same time. In Fig. 2(b), the unusual wafer movement is detected and confirmed by the built-in AE sensor. Figure 2(c) shows the response signal recorded by the VP-Probe. The amplitude of the probe suddenly and markedly increases simultaneously with the outbreak of particles in Fig. 2(a), and then fluctuates, maintaining its unstable condition for about 4 s. The result shows that the large and rapid change in floating potential on the deposited film occurs simultaneously with the sudden generation of many flaked particles from the deposited film; i.e., the films are strongly deformed and detached when the large and rapid changes in the floating potential occur. Then, the forced oscillation of a system under an external force due to such a potential change, which describes the displacement of the film, is analyzed [8]. The result reveals the instantaneous potential changes can lead to a sudden increase in electric field stress, which acts as an impulsive force. The films are seriously damaged by the impulsive force and then flake off in the form of a lot of particles. Such an instantaneous generation of particles is also observed when micro-arc discharge occurs [9]. Figure 3 shows an image of laser light scattered by particles, indicating many particles flaking off from the ground electrode although the micro-arc discharge occurs at the back of the wafer. The micro-arc discharge also gives rise to the instantaneous generation of numerous flaked particles because of the action of the impulsive force.

For the practical method to detect sudden generation of many particles, a high-speed and practical load impedance monitoring system is developed. The load impedance changes with the change in inner wall potential, so that the particle generation can be detected by the detection of the rapid change in the impedance. The impedance monitoring system employs a directional coupler connected in series between the rf power supply and the matching circuit; i.e., the sensor part is installed in the 50 Ω transmission line [10, 11]. The attenuated forward and reflected rf powers containing phase information are measured using the directional coupler and the Cross Domain Analyzer™ (ADVANTEST) in a wide measurement range from µW to kW without time delay. The load impedance, $Z_L = R_L + jX_L$, is the impedance of the load side seen from the output port of the matching circuit, where R_L and X_L are the real and imaginary parts of the load impedance, respectively, and j is the imaginary unit. Impedance monitoring software can be used to calculate the characteristic impedance, which involves not only the load impedance but also the impedance of the matching circuit including variable capacitors C_1 and C_2, hence the system simultaneously monitors these capacitances to separate the load impedance from the characteristic impedance by calculating the circuit equation. In other words, our monitoring system can directly measure the load impedance. The forward and reflected powers are recorded, and the load impedance is calculated at a rate of 10 MS/s for up to 100 µs. The time interval for the data acquisition is approximately 200 ms, which is the time needed for computing and displaying the results. The trigger system starts recording the forward and reflected rf powers only when a small reflected power caused by the arcing above an arbitrary threshold is

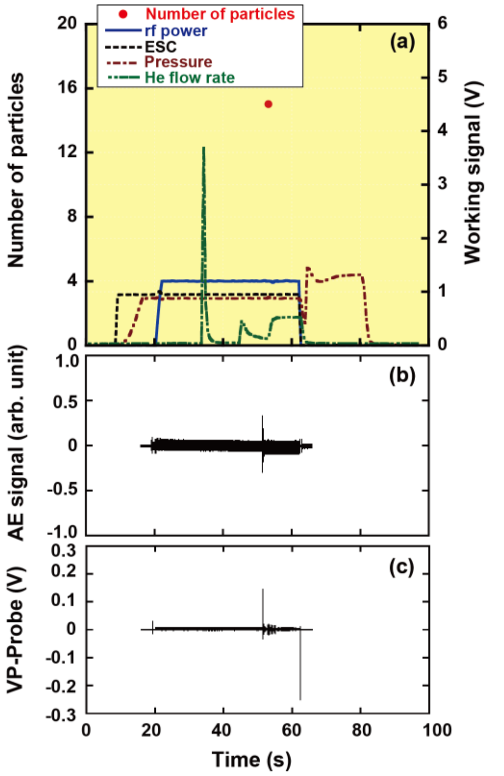

Fig. 2 (a) Relationship between the number of particles and the operation of etching equipment, (b) signal of AE sensor, and (c) signal of VP-Probe.

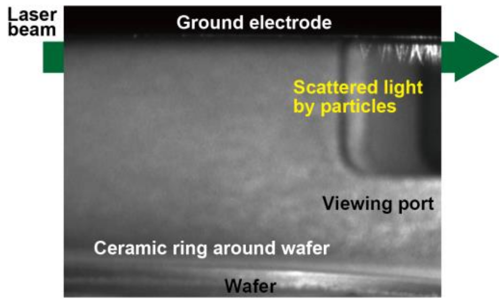

Fig. 3 Image of laser light scattered by particles.

detected. Figures 4(a)–4(d) are the results in the experiment of micro-arc discharge detection. The rf power is turned on at 0 s and shut down at 22.2 s, and the system is triggered 7 times during etching. After the plasma is stably generated, the values of C_1 and C_2 become stable, and R_L and X_L also become stable at approximately in the matching position. At 5.8 s, the system is triggered by the reflected power caused by the arcing. In Fig. 4(a), R_L suddenly and markedly changes from the matching value. At the same time, X_L also largely changes from the matching value as shown in Fig. 4(b). In contrast, the capacitance values in Figs. 4(c) and 4(d) do not respond to the arcing at all. The variable capacitors cannot be used for detecting the sudden changes in the impedance caused by micro-arc discharge because the capacitors are subject to the rotation rate of the stepper motors. Therefore, the results demonstrate that the system successfully detects micro-arc discharge from the 50 Ω transmission line.

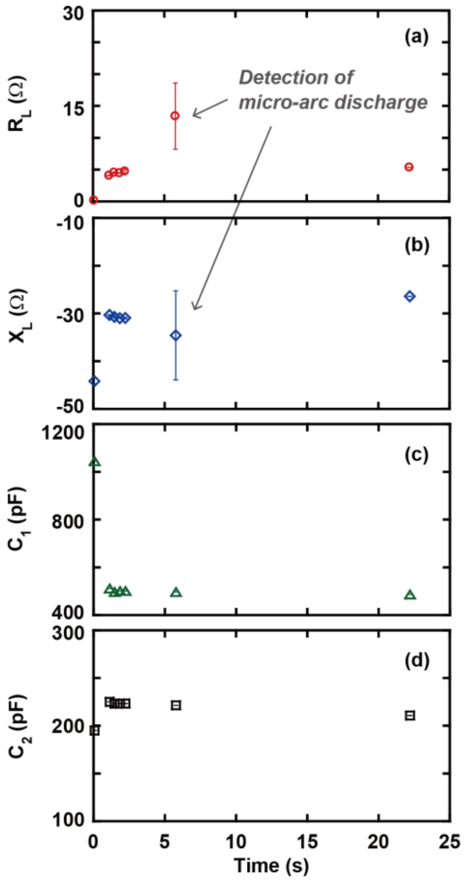

Fig. 4 Time variations of (a) real part of load impedance R_L, (b) imaginary part of load impedance X_L, (c) capacitance of variable capacitor C_1, (d) capacitance of variable capacitor C_2.

The mechanism of the instantaneous generation of many flaked particles is investigated under mass production condition. The results of this study reveal that the particles are generated by electric field stress acting as an impulsive force. The effectiveness of the novel load impedance monitoring system for the detection of the particle generation is demonstrated. This practical method can directly monitor the load impedance at high speed, and contribute to improving production yield and OEE.

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論文審査結果の要旨

プラズマエッチングで発生するパーティクルは、半導体量産ラインで歩留りや装置稼働率の低下を引き起こす最大の要因であり、量産ラインでは長年にわたって深刻な問題となっている。しかし、その発生メカニズムに不明な点も多く明確な原因が明らかにされていなかったことから、根本的な対策が困難となっていた。本論文は、特に深刻な問題の一つである剥離パーティクルの突発的多量発生について、その検出手法の開発と発生メカニズムの解明に取り組んだ研究についてまとめたもので、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章では実験方法を述べている。本研究では半導体量産ラインで使用されていた実機を使用することで実際の量産環境を再現し、剥離パーティクルの検出及びその発生メカニズムの解明に取り組んでいる。これまでのプラズマ中のダスト微粒子の研究では、意図的にチャンバに混入した微粒子を対象とする手法がほとんどであり、量産環境下での発生メカニズム解明に取り組んだ点に本研究の特色がある。剥離パーティクルの検出手法として、Mie 散乱を原理とする可視化システムを構築している。また本研究では、ウエハ跳ね（ウエハの吸着不良）に伴うプラズマ電位の急峻な変化が剥離パーティクルの突発的多量発生の一因であることを明らかにしているが、これまでウエハ跳ねの直接的な検出手法は存在しなかった。そこで、新たな手法として薄型 Acoustic emission (AE) センサ内蔵ウエハステージを提案し、その有効性を実証している。

第３章では、剥離パーティクルの突発的多量発生の検出結果を述べている。ウエハ跳ねや異常放電が発生した際にパーティクルが突発的に多量に発生すること、またその際にチャンバ内壁電位が急峻に変化していることを実験的に明らかにしている。これはパーティクル発生にプラズマ電位の急激な変化が関与していることを示唆しており、パーティクルの突発的発生メカニズム解明にとって有用な知見である。

第４章では、第３章で述べた実験結果に基づき、標準粒子を用いた原理的検証実験及び古典力学・衝撃工学における手法を導入した解析により、内壁電位の急峻な変化に起因して電場応力が撃力として作用するというメカニズムの存在を明らかにしている。更に、電場応力の撃力作用により堆積膜が急激に変形し、これが剥離しパーティクル発生の原因となるというメカニズムを提案するとともに、この検証実験を行い、撃力作用時には定常時よりも多量のパーティクルが発生することを証明している。

第５章では、第３、４章の結果に基づき、剥離パーティクル発生の原因となるプラズマ電位変化を測定することでパーティクル発生を検出する実用的手法の開発を述べている。量産装置の改造を伴わない検出手法として、プラズマインピーダンス測定システムの開発に取り組み、高速モニタリングが可能なその場検出手法を実現している。本測定手法は、シース部の静電容量やバルクプラズマの抵抗の変化を検出することを原理としている。本手法を用いることで、剥離パーティクルの突発的多量発生をもたらす内壁電位の急峻な変化により起こるプラズマインピーダンスの過渡的な変化の検出に成功し、突発的多量発生の検出手法としての有効性を実証している。本手法は、プラズマプロセス中にその場で異常を検出することが可能な極めて実用性に優れた手法であり、量産ラインにおける生産効率や歩留り向上に資する検出手法である。

第６章では、第５章で開発したプラズマインピーダンス測定システムの応用として、チャンバ内壁状態やシース部の静電容量の時間的変化がモニタリング可能であることを明らかにした。すなわち、本手法が量産装置の異常予知・保全手法として有効であることを実証している。

第７章は結論である。

以上要するに本論文は、剥離パーティクルの突発的多量発生の発生メカニズムが電場応力の撃力作用であることを初めて明らかにした研究であり、更に、突発的多量発生の検出手法として極めて実用的なプラズマインピーダンス測定システムを開発しており、電気・電子工学およびプラズマ理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。