Monitoring of Ultra-Trace Contaminants on Silicon Wafers for ULSI by a Novel Impurity Extraction and AC Surface Photovoltage Methods

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Monitoring of detrimental micro-contamination coming from various sources has been strived to upgrade process cleanliness in silicon (Si) ultra-large-scale-integration (ULSI), and to improve the device performance and chip yield. Processed wafers were investigated by means of chemical analytical and nondestructive ac surface photovoltage (SPV) methods. In this investigation, the pack extraction method (PEM), where sample wafers are enclosed in cleaned Teflon bags with aqueous acid solutions, were expanded to extract impurities. The PEM collect anions (SO_4^{2-} , NO_3^- , Cl^- , F^- , etc.), cations (NH_4^+ , Na^+ , K^+ , P^{5+} , B^{3+} , etc.) and detrimental metal impurities in Si wafers of both front and back surfaces, in contrast to the previously proposed technique⁽¹⁾. The PEM combined with ion chromatography and/or high resolution inductively coupled plasma mass spectroscopy facilitated to detect surface impurities to the level of 10^{12} – 10^{13} atoms/ m^2 which is equivalent to ppt in actual sample volume. Monitoring harmful impurities was successful in upgrading the cleanliness in Si wafers and device manufacturing processes. Based on the chemical analysis of SO_4^{2-} at wafer surfaces having inverted layers, ac SPV in n-type Si was found to decrease in proportion to increase in SO_4^{2-} concentration. SO_4^{2-} causes interface traps in native oxide, thus reducing the ac SPV. Hence, this nondestructive method is a useful technique for characterizing SO_4^{2-} as well as other metal impurities as proposed in the previous report⁽²⁾.

(Received March 18, 1996)

Keywords: silicon wafer, integrated circuits, process diagnostics, chemical evaluation, ultra-trace, micro-contamination, vapor phase dissolution, pack extraction method, Teflon bag, ion chromatography, inductively coupled plasma mass spectroscopy, ac surface photovoltage

I. Introduction

As device dimensions continue to shrink in ultra-large-scale-integrated (ULSI) circuits, there is a growing need for better control of heavy metal contamination⁽³⁾⁽⁴⁾. The wafer cleaning procedure in silicon (Si) device fabrication usually uses a combination of RCA (Radio Corporation of America) solution (alkaline and acid)⁽⁵⁾ and aqueous hydrofluoric acid (HF) solution with a small addition of hydrogen peroxide including surfactant⁽⁶⁾. Appreciable amounts of metal impurities (10^{13} – 10^{14} atoms/ m^2) still remain on finally cleaned Si wafer surfaces. Hence, the cleaning and its evaluation are major concerns and extensive investigations are being conducted. By improving micro-contamination during device processing, we expect to get higher yields in ULSI⁽⁷⁾.

In order to upgrade the yield for both incoming wafers and processed wafers in device fabrication, it is necessary to accurately measure ultra low levels of contamination on wafer surfaces. Recently, high resolution analytical methods which can sensitively detect ultra-traces of contamination are emerging. A typical method is inductively coupled plasma mass spectroscopy (ICP-MS) with a dou-

ble focusing magnetic sector mass analyzer⁽⁸⁾⁽⁹⁾. This kind of high resolution analytical instrument puts stringent demands on the sampling method intended to extract specific elements in a clean environment. The vapor phase dissolution (VPD) method⁽¹⁾ was proposed to collect metallic contaminants on Si surfaces as a droplet of acid by exposing the wafers to HF vapor in a clean, closed chamber. This method has been improved⁽¹⁰⁾ to make droplets of impurities segregated at the interface between Si wafer and liquid during wet cleaning⁽¹¹⁾. However, the VPD method⁽¹⁾ does not work for anion extraction for chemical analysis, because HF vapor does not create droplets of anion contaminants such as SO_4^{2-} and Cl^- on hydrophobic surfaces. Atomic absorption spectroscopy (AAS)⁽¹⁾, ICP-MS⁽¹²⁾ and total reflection X-ray fluorescence (TXRF)⁽¹³⁾, combined with the VPD were successfully applied for mirror surfaces excluding wafer edges and back surfaces in Si wafers. However, in the ULSI processes, micro-contaminations are often introduced at the wafer edge and back surfaces because of unexpected contacts with jigs or instruments. In monitoring such contaminations in its processes, it is highly desirable to accumulate the impurities from the whole wafer surface.

On the other hand, a pack extraction method (PEM)⁽¹⁴⁾ have been developed, where the sample wafer is packed in a clean double-layered polypropylene bag with hot water to extract impurities in air. In this investigation,

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the PEM has been expanded to extract metal impurities using three kinds of acid solution (HCl/H₂O, HF/H₂O, HF/HNO₃/H₂O) in a clean Teflon bag for various purposes; on surfaces, the oxide film and Si in the bulk. Compared with the VPD method, the PEM has the following features: (1) simultaneous extraction of impurities on both front and back surfaces of the wafers, (2) minimization of the environmental pollution during extraction once sample wafers are enclosed in the bag, (3) applicability for both anion and cation impurities in addition to detrimental metal impurities, and (4) it is easier to simultaneously treat many specimens in the same water bath. Therefore, our impurity extraction method described as PEM, which is combined with ion chromatography and ICP-MS, can be a strong monitoring tools on the Si wafer⁽¹⁵⁾ and device manufacturing processes. These results help to improve process cleanliness, resulting in upgrading the device performance.

As for diagnostic monitoring in device processings, a real-time non-contact approach has been aimed at characterizing the detrimental impurities on wafers. Recently, ac surface photovoltage (SPV) technique has become a strong tool for conducting nondestructive evaluation of Si wafers⁽²⁾⁽¹⁶⁾⁻⁽²²⁾. AC SPV arises when a depletion or inversion layer is formed at the Si wafer surface. Such a layer is caused by the charge-induced surface potential due to the positive charge in a p-type Si wafer or the negative charge in an n-type Si wafer⁽¹⁶⁾⁻⁽¹⁸⁾. Metal impurities such as aluminum (Al), iron (Fe) and copper (Cu) create negative charges on Si wafer surfaces⁽²⁾, while phosphorous creates positive charge⁽²³⁾. Thus, ac SPV can monitor such surface contaminations nondestructively by recognizing SPV signal heights and charge polarity, resulting in a contamination evaluation on the Si surface⁽²⁾.

This paper describes (1) the features of our impurity extraction method called as PEM, which is combined with ion chromatography and ICP-MS, (2) monitoring contaminants on both Si wafer and Si device manufacturing processes, aiming at improving process cleanliness for upgrading the device performances, and (3) an example of a nondestructive diagnostic method using ac SPV to detect anions (SO₄²⁻) on Si wafer surfaces on the basis of the chemical analysis data.

II. Experimental Procedure

1. Si wafers used for chemical analysis

Manufactured Si wafers 125 mm in diameter were prepared from Czochralski-grown <001>-oriented crystals. The wafers were phosphorus (P)-doped (n-type) or boron (B)-doped (p-type) to a resistivity of $105 \pm 15 \text{ m}\Omega\text{m}$ (P concentration $\sim 4 \times 10^{21} \text{ atoms/m}^3$, B concentration $\sim 1.6 \times 10^{21} \text{ atoms/m}^3$). Final cleaning of the wafers used for detecting contaminants was subjected to RCA alkaline solution (ammonium hydroxide/hydrogen peroxide/water) and/or acid rinse (hydrochloric acid/hydrogen peroxide/water)⁽³⁾.

2. Sample extraction for chemical impurities

Chemical impurities required at present for quality control in the Si device processes are anions (SO₄²⁻, NO₃⁻, Cl⁻ and F⁻), cations (NH₄⁺, Na⁺, K⁺, P⁵⁺, B³⁺, etc.) and metal impurities (Fe, Cu, Ni, Zn, Al, Cr, Co, etc.). The metal impurities were extracted in the form of an aqueous solution as described below.

(1) Anions and cations suspended in air

Three methods have been proposed for sampling anions and cations suspended as small particles in clean-room air environments, (1) bubbling (for $7.2 \times 10^3 \text{ s}$ at a flow rate of $1.67 \times 10^{-5} \text{ m}^3/\text{s}$) the sample air through purified water ($2 \times 10^{-5} \text{ m}^3$) using a impinger, (2) water in a beaker is exposed to the environmental air for about 48 h, (3) wafers are exposed to clean room atmosphere for a specified time and the accumulated impurities on the wafers are extracted by the PEM which is described below.

(2) Pack extraction method (PEM)

Impurities on both incoming and processed wafers are extracted in solution by PEM as follows. Figure 1 shows how the impurity extraction is carried out in six steps. (1)

Fig. 1 Procedure for impurity sampling at wafer surface by PEM (Pack Extraction Method) shown as follows in six steps; (1) cleaned PP bag (PP: polypropylene), (2) a sample wafer is put in PP bag, (3) pure water ($5 \times 10^{-5} \text{ m}^3$) or acid solution (10^{-5} m^3) is put in PP bag, and the PP bag is closed and sealed by heat, (4) a sample wafer is heated in a water bath (368 K, $1.8 \times 10^3 \text{ s}$), (5) after extracting impurities, wafer and solution are separated and sealed by heat, (6) extracted solution is introduced into ion-chromatography or ICP-MS.

A cleaned bag is prepared in a clean bench atmosphere. To enclose the wafers, double-layered polypropylene bags are used for anions and cations, and Teflon bags for metal impurities. (2) Sample wafers are enclosed in the bag, and (3) the bag is filled with $5 \times 10^{-5} \text{ m}^3$ of purified water for anions. For metal impurities, 10^{-5} m^3 of acid solution ($\text{HCl}/\text{H}_2\text{O}$, $\text{HF}/\text{HNO}_3/\text{H}_2\text{O}$) or 10^{-5} m^3 of HF solution ($\text{HF}/\text{H}_2\text{O}$) is put into the bag. HCl solution ($\text{HCl}/\text{H}_2\text{O}$) does not dissolve both oxide and Si but ionize metals in solution, as a consequence, it extracts metal impurities on the surface. HF solution dissolves the oxide and ionizes the impurities only in the oxide. HF/HNO_3 solution ($\text{HF}/\text{HNO}_3/\text{H}_2\text{O}$) extracts impurities in both oxide and Si bulk. Next, (4) the bags with various solutions are put into a water bath and kept at 368 K for $1.8 \times 10^3 \text{ s}$. After the treatment, (5) the extraction solution is pushed aside in the bag and separated by heat-sealing. (6) Sampling for the specified impurities is done externally under contamination-free conditions. During immersion of the wafers in the solution ($\text{HF}:\text{HNO}_3:\text{H}_2\text{O}=1:1:100$) or ($\text{HF}:\text{HNO}_3:\text{H}_2\text{O}=1:1:1000$) at about 368 K for $1.8 \times 10^3 \text{ s}$, the wafer bulk surface was etched away to a depth of about 0.1 or 0.4 μm , respectively. Chemicals used here were all for the electronics industry (EL-grade).

3. Chemical analysis

(1) Ion chromatography

For anion measurements, the sample water ($5 \times 10^{-6} \text{ m}^3$) was introduced into an ion chromatography (Dionex Co. 2010) column with an eluent solution of 0.0020 mol Na_2CO_3 /0.00075 mol NaHCO_3 . In a membrane suppresser, a regenerator (sulfuric acid 0.025 N) was used at a flow rate of $3.33 \times 10^{-8} \text{ m}^3/\text{s}$ to eliminate eluent ions, leading to improvement in sensitivity of conductivity monitoring by reducing the background raise. The detection limit of anions (SO_4^{2-} , NO_3^- and Cl^-) was about 10^{-11} kg in a 125-mm wafer. For cations, eluent solution (0.010 mol HCl) was flowed at the rate of $1.67 \times 10^{-8} \text{ m}^3/\text{s}$.

For metals, eluent solution (0.006 mol PDCA (2, b-Pyridinedicarboxylic Acid)/0.050 mol acetic acid/0.050 mol sodium acetate) is used at a flow rate of $1.67 \times 10^{-8} \text{ m}^3/\text{s}$. The post-column-reactor method is usually used for the metal detection, in which PAR (4-(2-Pyridylazo) resorcinol) reacts with metal ions, resulting in induced color. The metal concentration is measured by absorbency by irradiating with a light of wavelength 520 nm. The detection limit for impurities analyzed here is shown in the bar graphs in Figs. 3–5.

(2) Inductively coupled plasma mass spectroscopy (ICP-MS)

The ICP-MS (VG Co.; plasma trace (high resolution ICP-MS)) is provided with a double-focusing magnetic-sector mass analyzer. The sample solution is introduced into the analyzer at a flow rate of $1.67 \times 10^{-8} \text{ m}^3/\text{s}$. Acceleration voltage is 4.7 kV and plasma power is 1.3 kV. The resolution efficiency is 4500 for Fe, 2000 for Al, 3500

for Cu, Cr, Ni, and Zn. Ar is used as a neblizer gas at a flow rate of 0.9 l/min, auxiliary gas is 1.0 l/min, and cooling gas is 13 l/min. The detection limits for Al, Fe, Cr, Cu, Ni, Zn and Co are 4×10^{13} , 1×10^{13} , 9×10^{12} , 5×10^{12} , 2×10^{13} , 8×10^{12} and 2×10^{12} atoms/ m^2 .

4. Measurements of an ac SPV by SPM

In the present investigation, an in-house-developed scanning photon microscope (SPM)⁽¹⁹⁾⁽²⁰⁾ was used to observe ac SPVs in Si wafers.

Recently, several new instruments employing ac SPV have become commercially available for semiconductor characterization. These include the “Contamination Monitoring System” (CMS-III)⁽²¹⁾⁽²²⁾ and the “Surface Charge Analyzer” (SCA-2000)⁽²⁴⁾⁽²⁵⁾. The former instrument is characterized by a real-time, non contact approach. Also, Munakata *et al.*⁽¹⁹⁾⁽²⁰⁾ have reported the SPM based on the flying spot scanner function using two cathode ray (blue and infrared) tubes as photon beam (PB) sources. Both blue and infrared PBs were chopped at 2-kHz and irradiated onto the wafer surfaces to allow interface and bulk characteristics to be observed separately⁽¹⁹⁾⁽²⁰⁾. The induced ac SPV was capacitively detected through an air gap or a Mylar spacer between the wafer and a transparent electrode. Figure 2 shows an example of a scanning photon image of a p-type Si wafer oxidized for 58 h at 1173 K. The image was obtained by irradiation of infrared PB with wavelength peaks at 896 and 1076 nm. This picture reveals the distribution of oxide-precipitates originating in as-grown defects called, “swirl”. The dark ring corresponds to ring-shaped microdefects which can turn into stacking faults by further oxidation⁽²⁶⁾.

The SPM does not apply an electric field to the oxide, so charges in the oxide are unchanged. The time required to examine each wafer was 5 min in the normal operation mode and 1 min in the rapid mode.

Fig. 2 A scanning photon image obtained in an oxidized p-type Si wafer. Oxidation was done at 1173 K for 58 h in dry oxygen ambient. Probing was carried out using infrared photon beam in our in-house scanning photon microscope.

III. Experimental Results and Discussion

1. Surface impurities on Si wafer

Figure 3 shows concentrations of anions and cations of light elements at incoming wafer surfaces analyzed by ion chromatography for wafer vendors A, B and C. These measurements were obtained by PEM using deionized pure water at 368 K for 1.8×10^3 s. Anions on wafers are believed to be chiefly from the clean-room atmosphere after the final cleaning in the wafer fabrication processes. The concentration of Na^+ and K^+ is due to the use of alkaline solution (NaOH or KOH) for mechanochemical polishing. The origin of NH_4^+ is due to alkaline rinsing with NH_4OH or adhesion during cleanroom exposure after the final cleaning. The average level of contamination depends on the vendors (A, B and C) and is in the order of $\text{C} > \text{B} > \text{A}$. These results show the effectiveness of the cleaning technology of the air environmental conditions.

The concentration of metal impurities analyzed by ion chromatography is also shown for vendors A, B and C in Fig. 4. The impurities were extracted by the PEM using acid solution ($\text{HF}:\text{HNO}_3:\text{H}_2\text{O} = 1:1:1000$) at about 368 K for 1.8×10^3 s. The concentration of Al was measured with a graphite furnace atomic absorption spectrometer (AAS). For all impurities, the level of vendor B was much worse than for other vendors possibly because of the unoptimized final cleaning. Metal impurities are either incorporated into native oxide or adhere as particles on the surface. Cu ions precipitate on bare Si (hydrophobic surface) as neutral Cu by the reaction $\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}$, because the electronegativity of Cu is larger than that of Si. Those impurities come from the rinsing solutions: modified RCA-reagents and deionized water. The purity of reagents such as hydrogen peroxide plays decisive role in residual contamination on wafer surface. In particular, the electronegativity of Fe and Al is smaller than that of Si, thus being incorporated into a native oxide formed during modified RCA alkaline rinsing⁽²⁷⁾. In RCA alkaline rinsing with a Pyrex glass con-

Fig. 3 Concentration (C) of anions and cations of light elements at incoming wafers analyzed by ion chromatography for vendors A, B and C. DL means the detection limit of analysis.

Fig. 4 Concentration (C) of heavy metal at wafer surfaces for a few vendors represented by A, B, C. DL is the detection limit of ion chromatography for Fe, Cu, Ni, Zn and Co, and that of atomic absorption spectrometer for Al.

Fig. 5 Concentration (C) of heavy metal at wafer surfaces for a few vendors represented by A, B. DL is the detection limit of IC P-MS.

tainer, glass dissolves into solution, as a consequence, Al which is a major impurity in the glass enters the native oxide⁽²⁸⁾. Recently, Pyrex glass containers have been replaced with quartz containers. Thus, the surface contamination depends on the cleaning technology of each vendor; rinsing methods and the characterization techniques.

Because of the need of ultra-trace analysis in cleaned wafers, ICP-MS was used to measure them as shown in Fig. 5. The device characterization proved that the wafers with lower trace elements fitted satisfactorily the present ULSI processes.

2. Contamination of Si wafers in clean-room atmosphere

Figure 6 shows ion concentration levels in clean-room ambient extracted by the impinger method and analyzed by ion chromatography. Species of ions are linked with each fabrication line (represented by letters) and their processes (shown by hyphen followed by numbers). Cl^- , F^- , P^{5+} , and B^{3+} are generated by decomposition of reagent or by reaction with other materials. In the case of B^{3+} , the glass fiber in HEPA (High Efficiency Particulate Air) filter which consisted of B_2O_5 were attacked by HF

Fig. 6 Impurities in cleanroom atmosphere by analyzing wafers exposed for specific durations in various fabrication lines.

vapor, resulting in production of BF_3 . On the other hand, volatile P^{5+} ions contained in coating materials vaporize in clean-room environments. In the worst case, the concentration of P^{5+} in the air exceeded the order of $0.1 \mu\text{g}/\text{m}^3$. The B^{3+} and P^{5+} adhered to the bare Si area in circuit-pattern wafers, resulting in a change in the diffused concentration in the bulk between the top and bottom wafers loaded in batch-type diffusion furnaces, because of the difference in idling time (from 0.1 to around 1 h) before heat treatments. The boron and phosphorus atoms served as acceptor and/or donor dopants in Si substrate, thereby causing threshold voltage (V_{th}) variation in MOS transistors (for instance, ΔV_{th} due to the P-contamination was around 0.2 V and the scattering of the value increased across wafers depending on contaminated quantity). This result prompted countermeasures to cut off such contamination source.

On the other hand, SO_4^{2-} comes mainly from sulfurous acid gas originating in the combustion of a heavy oil. Figure 7 shows the seasonal change of SO_4^{2-} in the clean-room. The concentration of SO_4^{2-} was one order of magnitude higher in winter than in summer as expected. To prevent the ill effect of SO_4^{2-} on the breakdown of gate-oxide, a chemical filter has since been installed to catch such ions.

3. Metal contamination when handling Si wafers with manufacturing equipment

Figure 8 shows one monitoring example of heavy metals transferred to Si wafers when they were through various types of manufacturing equipment. These metal impurities were extracted by the PEM using acid solution ($\text{HF}:\text{HNO}_3:\text{H}_2\text{O}=1:1:1000$) at about 368 K for 1.8×10^3 s and analyzed by ion chromatography. The contamination potentially depends on processes on both front and back sides of wafers. The back side picks up impurities when it contacts part of equipment such as a chuck made of metal. In the sputter and dry etching processes, wafers are fixed by an electrostatic chuck made of stainless steel, resulting in seriously high contamination on back of the wafer. In diffusion processes, wafers are supported by a high quality quartz jig, thereby receiving lower contami-

Fig. 7 Seasonal fluctuation of SO_4^{2-} concentration (C) in clean-room air environments without chemical filter.

Fig. 8 Heavy metal contamination detected on wafers after passing through manufacturing equipment: stepper, sputtering and dry-etching equipment, and diffusion furnace. Numbers show types of equipment.

nation. Thus, the PEM is very useful for monitoring micro-contamination in the processed wafers. Heavy metals degrade minority carrier lifetime, for instance, Cu introduced by contact at the wafer edge diffuse into the bulk, resulting in refresh failure in dynamic memory devices⁽²⁹⁾. At present, wafer chucks and/or supports consisting of metals have mostly been replaced by clean non-metallic materials such as Teflon for $0.5\text{-}\mu\text{m}$ -rule devices or future state-of-the-art devices. Heavy contamination is removed at present by cleaning before gate oxidation. As a result, such metal contamination is reduced to less than $0.1\text{--}1 \text{ ng/wafer}$ ($10^{13}\text{--}10^{14} \text{ atoms}/\text{m}^2$), and this level is at present satisfactory for $0.5\text{-}\mu\text{m}$ devices⁽²⁾.

4. Nondestructive observation of SO_4^{2-} concentration by ac SPV method

Figure 9 shows the relationship between the ac SPV and the amount of SO_4^{2-} , indicating that the observed ac SPV is reduced in proportion to the total amount of SO_4^{2-} on n-type Si wafers. The ac SPV plotted was obtained from ac SPV profiles of the scanning photon images along the wafer diameter, and their average value (excluding those within 10 mm of the wafer edge) was taken as the observed ac SPV. In the present experi-

Fig. 9 Reduction of ac surface photovoltage with the concentration (C) of sulfuric ammonia (SO_4^{2-}) in n-type Si wafers rinsed with RCA alkaline solution in Pyrex glass containers prior to the air exposure in clean room environments.

ments, a 0.4-mm-diameter blue PB with a wavelength peak at 448 nm was used. The penetration depth was about $0.5 \mu\text{m}$. If the space charge layer is about $1 \mu\text{m}$, the PB excites excess carriers only in the space charge layer. The incident PB power was $4 \mu\text{W}$.

The surface layer of n-type Si wafers rinsed with a Pyrex glass container was strongly inverted by the induction of a negative charge due to $\text{Al}^{(20)}$. Here, those wafers were used as reference. As the concentration of SO_4^{2-} increased on wafer surfaces, the ac SPV decreased compared with the referenced values of ac SPV, implying that SO_4^{2-} acts as interface traps which compensate the net negative charge⁽¹²⁾⁽³⁰⁾. Since dense traps are believed to serve as a large charge reservoir for charges of the inversion layer⁽¹⁶⁾, the charge variation in the layer may increase with the higher amount of SO_4^{2-} , resulting in an increase in inversion capacitance. The ac SPV is almost inversely proportional to the inversion capacitance^{(16)–(18)}. This result indicates that the increase in SO_4^{2-} reflects the reduction in ac SPV in inverted n-type Si wafers. Thus, the ac SPV method is useful to nondestructively detect impurities which cause interface traps.

IV. Conclusion

Process diagnostics were performed to upgrade electrical characteristics in integrated circuits in silicon (Si) on the basis of a novel impurity extraction method which is named the pack extraction method (PEM). The PEM uses cleaned polypropylene bags with hot water or clean Teflon bag with an aqueous acid solution ($\text{HCl}/\text{H}_2\text{O}$, $\text{HF}/\text{H}_2\text{O}$, $\text{HF}/\text{HNO}_3/\text{H}_2\text{O}$) was effective for extracting metal impurities on both front and back surfaces of Si wafers for ULSI. The PEM combined with ion chromatography and/or high resolution inductively coupled plasma mass spectroscopy enabled us to detect the fluctuation of total contaminants on both manufactured and processed wafers to level of 10^{12} – 10^{13} atoms/ m^2 which is equivalent to ppt in actual volume. Anions (SO_4^{2-} , NO_3^- , Cl^- , F^- , etc.), cations (NH_4^+ , Na^+ , K^+ , etc.) and metal

impurities were monitored for incoming wafers. This result contributed to the feedback in the cleaning processes, thereby strongly influencing manufacturers to reduce detrimental metal impurities in wafers. The distribution of anions (SO_4^{2-} , Cl^- , F^- , P^{5+} and B^{3+} , etc.) in clean room environments (where SO_4^{2-} was due to the combustion of heavy oil) and B^{3+} produced because B_2O_3 in HEPA filters reacted with HF vapor, were controlled by partitioning each clean bay and/or by concurrently installing chemical filters. These countermeasures improved to prevent failure in devices such as gate oxide integrity and threshold voltage shift in MOS transistors. Based on the chemical analysis of SO_4^{2-} at wafer surfaces, ac surface photovoltage in n-type Si decreased in proportion to the increase in SO_4^{2-} concentration, because SO_4^{2-} causes interface traps in native oxide. Thus, this method was shown to be one of the useful techniques for non-destructive characterization.

Acknowledgments

The authors wish to thank Dr. Toshiaki Masuhara, Mr. Koichi Nagasawa, Mr. Akira Mogami and Dr. Masaki Nagao for their continued support and encouragement throughout the course of this work, and Dr. Yasuhiro Mitsui for his valuable discussions related to chemical analysis on Si wafer surfaces.

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