“MARORA” — A Plasma Selective-oxidation Apparatus for Metal-gate Devices

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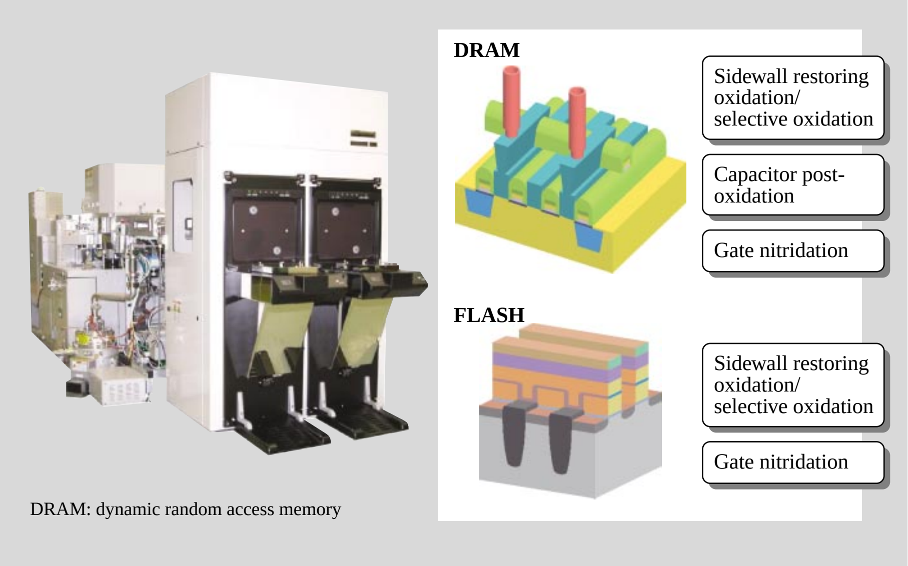
OVERVIEW: With the need to lower the temperature of semiconductor device processes being evident, plasma processing as an alternative technology to high-temperature processing is being investigated. At Hitachi Kokusai Electric Inc., stealing a lead over our competitors, we have commercialized an apparatus for plasma selective-oxidation — a process that accompanies the adoption of metallic materials for transistor gate electrodes — and installed it on device fabrication lines. An MMT plasma method and a plate-type high-temperature heater are basic technologies used in this selective oxidation. In particular, wafer temperature is increased considerably compared to that for a conventional plasma apparatus, and the interface-state density in the oxide film is decreased by more than 30%. From now onwards, aiming to satisfy our customers’ needs, we will continue to vigorously push ahead with equipment and process developments based on these basic technologies and, in doing so, contribute to further evolution of semiconductor devices.

INTRODUCTION

AS a consequence of the refinement of semiconductor devices, development of new materials and revision of device manufacturing methods are currently under investigation. Under these circumstances, the demand to lower temperatures involved in device fabrication processes is getting stronger. In addition, in regard to film-formation processes, the development of technology for forming high-quality thin films at low temperature is going ahead at full speed.

Given this background, in 2001, Hitachi Kokusai Electric Inc. started manufacturing single-wafer-plasma nitridation and oxidation equipment. Since then, we have built up a successful record of deliveries to customers centered on improvement of DRAM (dynamic random access memory) capacitor insulator films and applications of gate-oxide-film nitridation and high-*k* gate nitridation(1). As alternative technology to high-temperature processing equipment that performs processing at wafer temperature in the range



DRAM: dynamic random access memory

Fig. 1—External Appearance of “MARORA” Plasma Selective-oxidation Equipment and Main Application Processes for Memory Devices.
Hitachi Kokusai Electric Inc. has developed selective-oxidation equipment as a basic technology for MMT (modified magnetron typed) plasma technology and a plate-type high-temperature heater. MARORA is also being investigated in regard to application to a number of other semiconductor processes other than selective oxidation.

of 200 to 450˚C, plasma processing equipment is under investigation. At the same time, plasma-processing equipment is under investigation as alternative technology for replacing high-temperature thermal processing at wafer-temperatures above 850˚C. And the demand for plasma thin-film-formation technology that can perform processing in the temperature range from 450 to 850˚C is growing.

In the rest of this report, a plasma selective-oxidation apparatus, called "MARORA," for handling metal-gate electrodes — which was developed under the circumstances surrounding the customer needs described above — is described (see Fig. 1).

TECHNICAL CHALLENGES AND COUNTERMEASURES CONCERNING THE SELECTIVE-OXIDATION PROCESS

As semiconductor devices have been refined more and more, in regard to the gate electrode of transistors, cell size has been shrinking and electrode resistance has been rising. Consequently, in certain devices with a silicide film (an improved electrode material compared to poly-silicon), metal electrodes such as tungsten are being adopted.

At the same time, on forming transistor cells, the etching processes — from gate-electrode formation to gate-insulating-film formation — are performed in block. On the processed surfaces produced by this processing sequence, etching damage occurs; therefore, "damage-restoration oxidation" is performed directly after etching. However, the metal electrode is easily oxidized, and the insulation film resulting from that oxidization has an increased resistance compared to that of the metal electrode. As a result, during the damage-restoration oxidation, selective-oxidation technology for selectively oxidizing silicon without oxidizing the metal electrode is required.

As technical challenges facing this selective-oxidation technology, the following three tasks must be accomplished.

(1) Suppression of "bird's beak" (i.e. suppression of oxidation of poly-silicon electrode edge interfaces)

(2) Restoration of etching damage

(3) Assurance of selectivity between metal electrode and silicon

However, in the case of high-temperature oxidation processing (i.e. over 850˚C) used in conventional semiconductor fabrication processes, it is known that the edge-interface boundary of the poly-silicon electrode is oxidized, and the gate-oxide film gets thicker, thereby degrading the characteristics of the semiconductor device(2).

Facing up to these technical challenges, Hitachi is pushing ahead with development of equipment that can perform plasma-oxidization processing at the highest temperature possible without generating the bird's beak phenomenon and its commercialization after evaluation periods at research centers of various device manufacturers. In particular, we are offering tangible solutions for

(1) suppression of bird's beak by thermal-budget reduction under single-wafer-plasma oxidation processing,

(2) formation of high-quality plasma-oxidation film through development of a plate-type high-temperature heater, and

(3) assurance of selectivity by tuning of process conditions and process sequence.

EQUIPMENT DEVELOPMENT CONCEPT

Plasma Generative Mechanism and Equipment Configuration

The plasma source uses MMT (modified magnetron typed) plasma technology, which was jointly developed with Tohoku University. As a special feature of an MMT plasma source, it is possible to generate a uniform plasma from a large diameter at high density and across a wide pressure range and to produce "damage free" processing by means of a low electron temperature (i.e. < 1 eV)(3). Furthermore, the structural components of the reaction-chamber inner surface that contacts the plasma use high-purity-quartz elements, and metallic contamination is reduced to a minimum.

What's more, an in-line-type platform is adopted as an equipment configuration, the equipment footprint in a two-chamber configuration is small (i.e. 6.6 m^2), and processing at 50 wafers per hour is possible by means of a high-speed conveyor system.

Development of Plate-type High-temperature Heater

The main material in a conventional plate-type high-temperature heater is aluminum nitride. The problem of strength resistance to thermal stress means that heater temperature is limited to 600˚C and wafer temperature is limited to 450˚C. Given those limitations, we have reviewed the main material for the heater. That is to say, by developing heater-fabrication technology and optimizing heater-element materials and patterns by simulation, we developed a plate-type high-temperature heater that can raise wafer temperature to a considerably higher temperature than possible with a conventional heater.

Assuring Selectivity

For oxidizing the silicon surface without oxidizing the metal electrode, the reduction function of hydrogen is utilized. Although the process gas used for this reduction is a mixed gas containing hydrogen, the reaction that takes place at that time is a combination of simultaneous oxidation and reduction. To achieve selective oxidation, it is necessary to execute the process under the conditions that the oxidation reaction becomes dominant for silicon but the reduction reaction becomes dominant for metal. Since these conditions vary according to process conditions other than gas ratio (such as radio-frequency power and temperature), the process window must be understood through experiments and optimized.

PERFORMANCE OF PLASMA SELECTIVE-OXIDATION EQUIPMENT

Temperature Dependence of Plasma-oxidation-film

To solve the above-described technical problems concerning the selective-oxidation process, we have developed a plate-type high-temperature heater that can raise wafer temperature considerably higher than that possible with a conventional heater (i.e. 450˚C). The dependence of interface state density of a plasma-formed oxide film on wafer temperature is plotted in Fig. 2. The figure shows that the interface state density strongly reflects the film’s properties, and when it is low, a film with high quality is formed. It is also confirmed from the figure that the interface state density becomes lower toward the high-temperature processing (right) side of the graph. To put that concretely, the interface state density of an oxide film produced by the high-temperature heater is about 35% lower than the corresponding value for a conventional heater. It can thus be understood from this result that a high-quality oxide film can be produced by our new high-temperature heater.

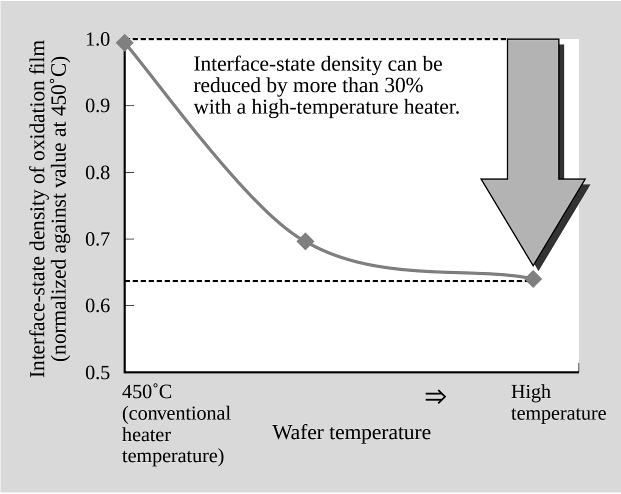
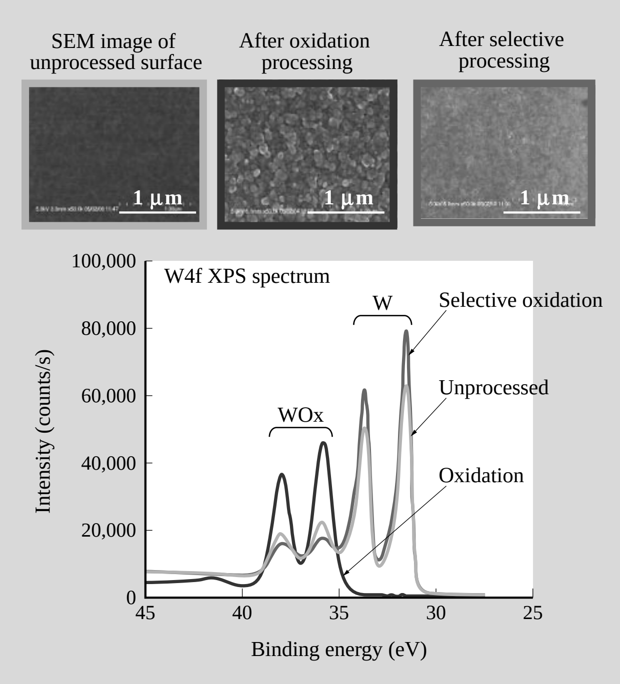


Fig. 2—Dependence of Interface-state of Oxidation Film on Wafer Temperature.
Results are normalized against interface-state density at 450˚C (i.e. wafer temperature in conventional heater). It is confirmed by the graph that interface-state density decreases as wafer temperature increases and, in particular, it can be decreased by more than 30% with development of a high-temperature heater.

Verification of Selectivity

The process window for assuring selectivity varies according to the kind of metallic materials used. An evaluation result on the selectivity for tungsten is shown in Fig. 3. The surface SEM (scanning electron microscope) image in the center shows the top-surface structural state produced by normal oxidation processing without selectivity. It confirms variations in a manner that crystal grains are formed on the



SEM: scanning electron microscope
XPS: X-ray photoelectron spectroscopy

Fig. 3—Evaluation Results Concerning Selectivity for Tungsten.
According to the upper SEM images, unprocessed sample and unchanged surface features are maintained with selective oxidation. According to the XPS spectra, the WOx peak (tungsten oxide) shrinks after selective oxidation, thereby confirming that tungsten is not oxidized.

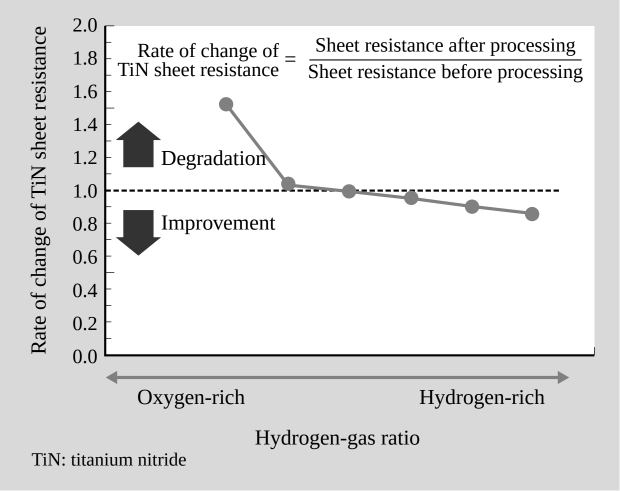


Fig. 4—Rate of Change of TiN Sheet Resistance with Increasing Hydrogen Ratio.
By making the gas ratio more hydrogen-rich, the sheet resistance of the TiN film after oxidation processing can be reduced.

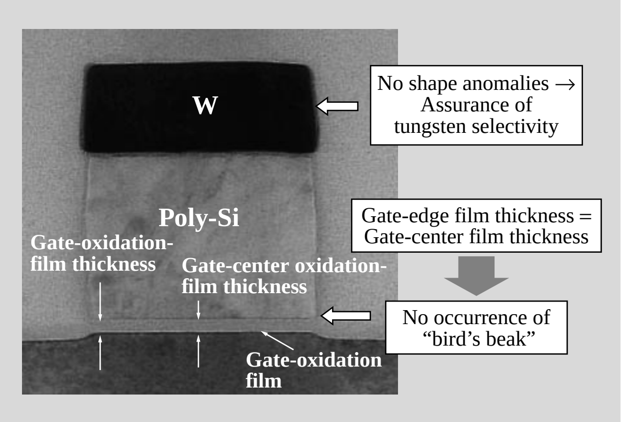


Fig. 5—Cross-sectional-TEM Assessment of Shape Formed by Selective-oxidation Processing.
After oxidation processing, no shape anomalies can be seen in tungsten electrode. Moreover, oxidized-film thicknesses of gate edges and gate center are unchanged, and "bird's beak" (i.e. increased thickness of the oxidized-film edges due to re-oxidation of poly silicon) does not occur.

tungsten surface. The SEM image on the right confirms that the top-surface state that is expressed after selective-oxidation processing is unchanged in comparison to the top-surface state of the unprocessed sample.

Furthermore, the graph in the lower half of Fig. 3 shows that the WOx (tungsten oxide) peak in the W4f XPS (X-ray photoelectron spectroscopy) spectra shrinks after oxidation processing. In addition, the figure confirms from the elemental-analysis results on the top surface that selectivity is attained. In the case that the metal electrode is TiN (titanium nitride), oxidation is easier than in the case of tungsten, and the process window for assuring selectivity becomes narrow. Fig. 4 shows the rate of change of TiN sheet-resistance value when the hydrogen proportion in the process gas is increased. Although sheet resistance of the TiN film increases as oxidation of the film progresses, it is confirmed that the rise in sheet resistance after selective-oxidation processing can be suppressed by increasing the hydrogen proportion in the process gas. In the case of other materials (such as tungsten nitride and tantalum nitride), it is also confirmed that oxidation can be suppressed.

The result of an evaluation by cross-sectional TEM (transmission electron microscopy) of the shape formed after plasma selective-oxidation processing is shown in Fig. 5. Although the gate electrode utilizes tungsten, even after oxidation processing, abnormalities in the external appearance are not seen, and even selectivity on the pattern is not a problem. Moreover, the magnitude of the variation in the thickness of the central part and edges of the oxide film is below the detection limit of the TEM image, and it is confirmed that "bird's beak" is suppressed.

Evaluation Results on Device Application

Selective-oxidation technology using MARORA is being evaluated by device manufacturers, and they have confirmed that the technology is favorable even in regard to transistor characteristics(4).

In the 60-nm technology generation, even if a metal electrode is used, a CVD (chemical vapor deposition)-deposited film can be capped on the metal electrode, and the oxidation of the metal can be suppressed by devising a device fabrication process. However, in accord with further scaling down into the generations beyond the 50-nm one, without capping with a CVD film, it will be necessary to perform selective oxidation without oxidizing the metal electrode. Taking the lead over our competitors, we are building up our achievements regarding installing MARORA in device fabrication lines. What's more, it is considered that basic technologies for forming transistors with a high-*k*/metallic structure will be required. From now onwards, therefore, while the multiplying the number of metal gates, it is expected that MARORA will function as a key process technology.

CONCLUSIONS

In regard to a plasma selective-oxidation apparatus — called MARORA — for handling plasma thin-film formation on a metal-gate electrode, this report described its commercialization through establishing a technology for improving the quality of the oxide film (by applying a newly developed plate-type high-temperature heater) and a technology for selectively oxidizing silicon only. As a result of lowering the temperature of semiconductor fabrication processes, up till now, the substitution of many processes that have been executed under high-temperature heating with plasma methods has been investigated, and it is forecast that applications of plasma processing will keep multiplying. At Hitachi Kokusai Electric Inc., handling technology trends in semiconductor devices in an appropriate manner, we will continue process development and equipment development to satisfy our customers' needs and, in doing so, contribute to the evolution of semiconductor devices.

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