Plasma Oxidation and Nitridation System for 90- to 65-nm Node Processes

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OVERVIEW: In meeting the ever more advanced needs of semiconductor device fabrication processing, Hitachi Kokusai Electric Inc. has now developed an MMT (modified magnetron typed) low-temperature plasma processing system that is capable of meeting the demanding process windows for the next two generations, 90-nm and 65-nm technology nodes. Employing an MMT plasma source that generates soft plasma at an electron temperature of under 1 eV, Hitachi's plasma surface processing system deposits thin films over extremely fine featured semiconductor devices at low temperature and with excellent uniformity. More specifically, the system performs nitridation processing while depositing a high-quality oxide layer as the gate dielectric, the heart of the transistor, and is capable of depositing films with an EOT (equivalent oxide thickness) of less than 1.2 nm that is required by the generation after next 65-nm technology node. Compared to other kinds of plasma sources, the MMT low-temperature plasma processing method described here consumes relatively little power (about 1/10 the power consumed by other methods), and thus represents a new generation of semiconductor fab processing equipment that is environmentally friendly. This system will open the way to a wide range of 65-nm node and beyond future semiconductor processes enabling higher performance transistors through pre-processing of high-k films, formation of flash memory ONO (oxide-nitride-oxide) structures, deposition of capacitance dielectric films for DRAMs (dynamic random access memories), and deposition of thin films for VLSIs (very-large-scale integrated circuits).

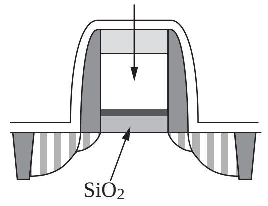
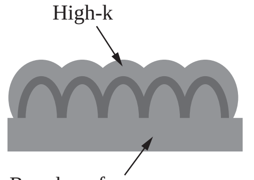
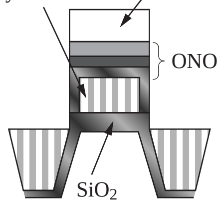
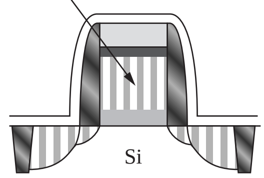
INTRODUCTION

THE demand increases for the reduction of high-temperature device fabrication processes as VLSI (very-large-scale integrated circuit) technology evolves toward smaller features. Plasma can be used to accomplish the same things as high-temperature processing but at a much lower temperature, and is therefore finding increased applications in the fabrication of semiconductor devices. Plasma only requires an electron temperature of 1 eV to activate gas which corresponds to thermal process temperature of 10,000°C, so even gases that exhibit poor reactivity in thermal energy nevertheless react readily with activated in plasma. Using oxygen and nitrogen plasmas, a wide range of films can be oxidized and nitridized in a short time at low temperatures ranging from room temperature to 400°C.

This article presents an overview of the MMT (modified magnetron typed) plasma oxidation and nitridation system, and surveys some of its most promising applications (see Fig. 1).

OVERVIEW OF MECHANISM AND APPARATUS FOR GENERATING MMT PLASMA

In a cooperative development projects with the laboratory of Professor Noriyoshi Sato of Tohoku University, Hitachi Kokusai Electric Inc. has developed a plasma oxidation and nitridation system that uses an MMT plasma source. In contrast to the plasma sources used in the past, MMT plasma is produced using an MMT RF (radio-frequency) discharge method featuring a newly devised cylindrical multipolar magnetic field electrode. Essentially, this discharge

	Gate oxidation, nitridation	Capacitor interface nitridation	Flash memory oxidation, nitridation	High-k interface oxidation, nitridation
Need	• Leakage current control • Equivalent oxide thickness • Prevent boron penetration • Damage-free plasma	• Prevents oxidation of bottom electrode • Lower thermal processing (< 600ºC) • High step coverage • Damage-free plasma	• Suppress leakage current • Film thinning • Enhance reliability • Damage-free plasma	• Prevent Si surface oxidation • Reduce interface states • Prevent boron penetration • Damage-free plasma
Structure				

: MMT nitridation : MMT oxidation

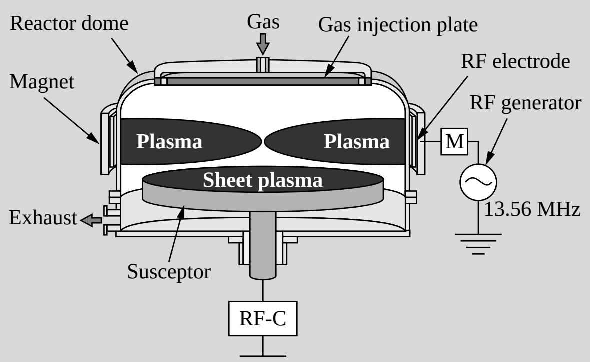
ONO: oxide-nitride-oxide

Fig. 1—Overview of Applications and Needs for MMT Plasma Source.
A commercial version MMT plasma processing system has been successfully developed that is capable of depositing transistor gate dielectric films, the core of the next two generations (90- to 65-nm nodes) of VLSI devices.

mechanism produces high-density wide area uniform plasma over a wide pressure range[1, 2] (see Fig. 2).

The MMT reactor generates magnetron discharge plasma through interaction between magnetic lines of force from a permanent magnet and RF electric fields applied to a ring-shaped RF electrode. The MMT plasma exhibits excellent stability and uniformity, and also generates damage-free plasma because the electron temperature near the substrate is less than 1 eV. In the case of MMT plasma, the plasma electron temperature on the substrate surface is practically independent of the RF power entering the reaction chamber. This means that a low electron temperature is maintained even when the plasma density is increased to a high level by high RF power. In addition, the energy of the ions impinging on the substrate surface can be controlled over a wide range by adjusting the RF-C (radio-frequency impedance control mechanism) provided on the lower part of the susceptor.

The plasma surface processing system was designed based on the bridge tool concept, and thus can be easily adapted to either 200-mm and 300-mm substrate processing by changing some parts. The reaction chamber can also be adjusted from 200-mm to 300-mm capacity by changing the susceptor. An in-line type platform is adopted for compact high-speed conveying: the throughput for a single oxidation and nitridation process in one chamber is 25 wph (wafers per hour). The platform that is now commercially available permits two chambers to be connected, and



M: matching box

Fig. 2—Schematic View of MMT Reaction Chamber.
The system provides damage-free application of plasma, good control over ions impinging on the substrate, and excellent uniformity and reproducibility of plasma.

the equipment footprint is quite small at 6.6 m^2 (see Fig. 3). We are now working on conveying system that will support up to 4 interconnected chambers for polysilicon doping, high-k deposition, RTP (rapid thermal processing), and other process modules to be integrated.

MMT PLASMA SOURCE APPLICATIONS

Thin-film Gate Dielectric Plasma Oxidation and Nitridation for 90- to 65-nm Technology Nodes

Conventional high-temperature oxidation processes tend to produce lattice defects, and that can cause rediffusion of impurities in devices that are already formed. Also, the trend toward increasing wafer size, the possibility of warpage by high-temperature processing cannot be ignored. In order to deposit a uniform thin film over a 300-mm substrate, certainly a lot of ingenuity goes into the equipment, but it is desirable for the process to use as little activation energy as possible so that any adverse effects of the oxidation reaction itself due to variations in temperature are minimized.

When the MMT plasma source is used, a mixture of oxygen and inert gas is mixed to produce the plasma, then the LSI (large-scale integration) gate oxide layer is formed by subjecting the silicon substrate to oxidation processing at temperatures below 400°C. While maintaining a surface uniformity within ±1.5%, films are deposited with excellent reproducibility ranging from 0.8 to 4.0 nm in thickness by just varying the processing time. Not only has the temperature of the processing been reduced, we also found that the quality of the deposited oxide film is equivalent or better than oxides deposited by a high-temperature process (see Figs. 4 and 5).

As circuits have become faster and device dimensions smaller, the demand for thinner gate dielectric films has continued to increase. The problem is that it becomes increasingly difficult to ensure device

Fig. 3—Appearance of MMT Plasma Surface Processing System.
Based on a 200/300-mm bridge tool concept, Hitachi's processing system provides a high throughput yet has a relatively small footprint.

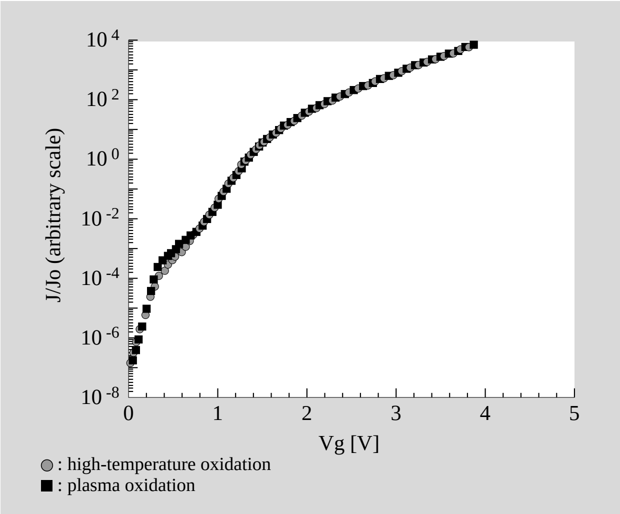


Fig. 4—Comparison of Leakage Current of MMT Plasma Oxidized Film and High-temperature Oxidized Film.
It is apparent that the leakage current of the MMT plasma oxidized film is equivalent to that of the high-temperature diffusion oxidized film.

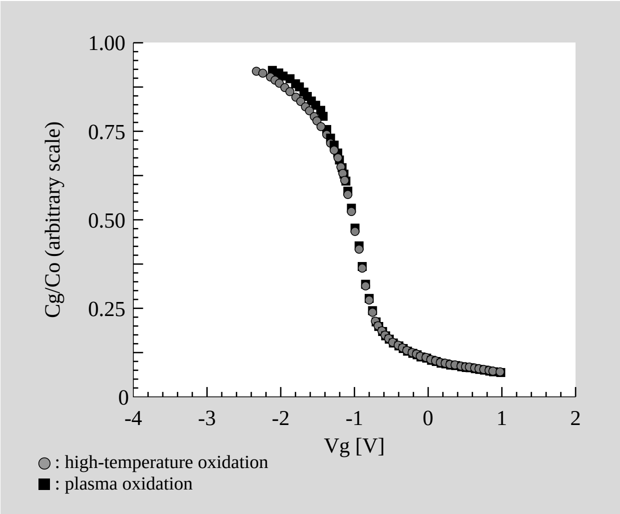


Fig. 5—Comparison of Gate Dielectric Film Capacitance of MMT Plasma Oxidation Film and High-temperature Oxidation Film.
Capacitance of the MMT plasma oxidized film is equivalent to that of the high-temperature diffusion oxidized film.

reliability due to a worsening TDDB (time-dependent dielectric breakdown) characteristic, and this causes device performance to suffer as a result of stress-induced leakage current. Furthermore, boron penetrating resistance is compromised when boron-doped gate electrodes are used, and this increases device performance inconsistency. To accommodate the shift to cutting-edge 90-nm node devices and beyond, strong demand has emerged for processes that are able to reconcile high performance based on thin-film oxidation technology for gate dielectric with reduced power consumption. One solution that looks especially promising is the approach described here of using nitrogen plasma for nitridation of the gate oxide.

The MMT plasma machine controls the difference between the plasma space potential and the substrate surface potential by regulating the RF impedance of the susceptor. In the nitridation process of the gate oxide, by applying high concentrations of nitrogen on the surface of the oxide layer and controlling the profile of the nitrogen in the depth direction, the nitrogen at the interface between the oxide layer and the silicon can be reduced and the nitridation process can proceed without adversely affecting the transistor characteristics of the device. When MMT plasma is used, the gate oxide layer is formed using exactly the same hardware by just changing the plasma gas. This means that the oxidation and nitridation of the gate oxide layer can be carried out sequentially in the same reaction chamber, thus permitting the contamination of the gate interface layer to be kept to an absolute minimum, which should result in better device characteristics. Thanks to this sequential oxidation and nitridation processing in the same MMT reaction chamber, deterioration of device mobility in thin oxidation and nitridation gate dielectrics is prevented, the EOT (equivalent oxide thickness) is reduced to under 1.2 nm, leakage current is reduced by more than an order of magnitude compared to pure oxide, and the prospects are excellent that this approach can also be applied to the generation after next 65-nm technology node. Another benefit is that the plasma damage to the substrate caused by MMT plasma is minimal, so that excellent device characteristics are obtained without the need for post-anneal processing to repair the plasma damage even after oxidation and nitridation when the temperature is kept below 400°C. There is also no need to add argon or any other dilution gas, and a stable plasma is generated at low power with nitrogen alone.

APPLICATION TO THE FORMATION OF DRAM CAPACITOR DIELECTRIC FILMS

Oxide and nitride layers can be deposited on silicon for thicknesses ranging from 0.5 to 5.0 nm at temperatures below 400°C while maintaining a surface uniformity of ± 2%. MMT provides extremely high plasma generation efficiency, so oxidation and nitridation proceed very quickly at low RF power. And since plasma oxidation and nitridation processing involves a surface substrate reaction that accompanies a gas phase reaction, the oxidation and nitridation observe excellent conformity even to patterns with the most demanding aspect ratios. The mainstream method of forming DRAM (dynamic random access memory) capacitor dielectric films having a trench structure has always been to deposit nitride and oxide layers in a stacked structure. In the past, nitride layers have generally been formed by LP-CVD (low-pressure chemical vapor deposition), but leakage current due to pin holes has became increasingly problematic, so the limits of CVD have now already been reached. Hitachi Kokusai Electric Inc. is currently investigating whether the plasma nitridation and oxidation technology can be applied for the formation of trench capacitor dielectric layers.

In the case of DRAMs and mixed memory devices where processes employ high-k films such as Ta_2O_5 for the memory dielectric film, it was found that

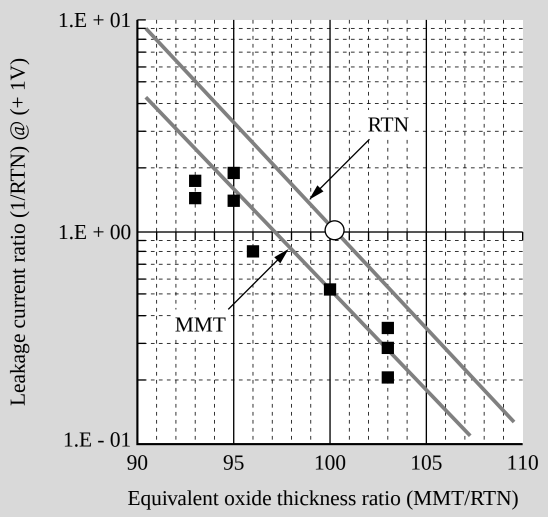


Fig. 6—Leakage Current Reduction Effect.
Overall leakage effect of high-k capacitor dielectric layer (Ta_2O_5) formed by high-temperature nitridation and by an MMT nitrogen plasma.

applying low-temperature plasma nitridation to the bottom electrode surface before depositing the high-k layer was quite effective for reducing the thermal budget and improving device performance. We also discovered that low-temperature oxide plasma processing was extremely effective for improving film quality after the deposition of a high-k film (see Fig. 6).

Other Applications

When fabricating flash memory tunnel gates, oxide layers are subjected to nitridation processing to suppress deterioration that occurs over time, but the reliability of tunnel gate films was significantly enhanced by using MMT nitrogen plasma for the nitridation. Plasma oxide can also be applied in the formation of ONO structures on floating gate electrodes.

We are now investigating the use of high-k materials for the gate dielectric in CMOS devices for microprocessor units and for the 45-nm technology node and beyond. A thin interface layer must be deposited between a high-k film and the silicon substrate to ensure good device electrical characteristics, and for this purpose we anticipate that the thin oxide layers and nitrided oxide layers formed by MMT plasma will serve very well as barrier layers. After high-k films have been deposited, it is necessary to remove impurities from the film at low temperature, to supply oxygen, and to apply plasma processing to the contact surface with the gate electrode, and low-temperature processing by MMT plasma should fulfill these tasks very well.

CONCLUSIONS

In this article we described an MMT plasma oxidation and nitridation machine, and surveyed some of the main applications for the system.

We determined that gate oxidation and nitridation based on the modified magnetron typed RF plasma generation approach described in this paper appears to be capable of meeting the process windows for the 65-nm technology node. The technology is very promising for practical deposition of DRAM capacitor dielectric films, for application to flash processes, for pre- and post-processing of high-k dielectric films of the future, and will likely be adopted for many other applications where low-temperature processing is called for.

The MMT plasma oxidation and nitridation system features low power consumption and is environmentally friendly, and therefore contributes to conservation of the global environment. The Hitachi Group plans to further enhance and upgrade the MMT plasma oxidation and nitridation system to meet the evolving needs of the semiconductor manufacturing industry.

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