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Effect of Ceria Abrasives on Planarization Efficiency in STI CMP Process

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The strong Ce-O-Si bonding between CeO₂ abrasives and SiO₂ film surface; i.e., the chemical tooth effect, improved planarization efficiency in CMP using ceria-based slurry as a result of nonlinear behavior of the removal rate. Removal rate is a power function of pressure and relative velocity (i.e., $RR = kP^\alpha V^\beta$). In particular, the high dependency of removal rate on pressure when $\alpha > 1$ results in a much higher material removal rate in the upper pattern than in the lower pattern. Therefore, the planarization efficiency of ceria-based slurry is better, from initial polishing time to the completion of the polishing step, than that of conventional silica-based slurry with an exponent value of $\alpha \approx 1$.

Introduction

Chemical mechanical polishing (CMP) was initially introduced into semiconductor processing to planarize interlayer dielectrics [1], and therefore oxide CMP has been the most widely used process in the fabrication of IC chips such as DRAM, Flash, MPU, and ASIC. In particular, shallow trench isolation (STI) CMP has recently become a key technology for electrical isolation between transistors as the minimum feature size shrinks down to the sub-45nm level [2]. However, it is not easy to uniformly planarize the oxide feature on silicon wafer with nano-topography [3]. A pattern with various sizes also affects the planarization of die-scale and wafer-scale. Thus, the STI CMP process requires a high planarity slurry, while the oxide CMP process has generally adopted an alkaline slurry with silica abrasives. Slurry with ceria abrasives has effectively solved the demand in the IC industry, due to its high removal rate and planarization efficiency [4-6].

Currently, the CMP process for STI formation consists of two steps: first, a planarization process of oxide topography, and second, a damascene process after planarization. In the first CMP step, the conventional slurry consists either of alkaline silica-based slurry or neutral ceria-based slurry to only removal the SiO₂ pattern. However, ceria-based slurry has been more widely used to achieve high planarity than silica-based slurry [6,7]. In the second CMP step, the high selectivity ceria slurry is used, because the ratio of the removal rate of SiO₂ and Si₃N₄ in CMP using silica-based slurry is not sufficient. The ceria slurry can substantially reduce the non-uniformity of remaining silicon nitride over the wafer surface. The variation of thickness of field oxide can also decrease because of effective nitride stop during the CMP process [6,8]. If the SiO₂ surface after the first CMP step has bad planarity and nonuniform thickness across the wafer-scale, it will induce worse polishing results after the second CMP step.

Therefore, the first step of STI CMP is very important to achieve good planarization, and thus should be strictly controlled by using ceria-based slurry.

A typical slurry for the oxide CMP process contains 10~13 wt% silica abrasive concentrations. The slurry pH is also about 11 because of alkaline additives. The oxide CMP mechanism of silica-based slurry is based on the interactions of water molecules with SiO₂ surface in the glass polishing process. Tomozawa [9] mentioned that the primary mechanism of oxide CMP consisted of the fracturing or softening of oxide films at elevated temperatures by the friction force generated during CMP, which is accompanied by plastic deformation of the surface due to hydration by diffusion of water molecules. The softened oxide layer is subsequently plowed by abrasive particles in the silica slurry.

In comparison with silica-based slurry, a typical ceria-based slurry contains a low abrasive concentration of 1~3 wt% in neutral solution. It is also reported that the ceria particles are about three times denser than silica particles [10], which usually leads to particles settling in the dispersed state. Furthermore, ceria particles are softer than silica particles [7]. If the mechanical effect of ceria is dominant, the softer particle should give a low removal rate; however, this is not true. In fact, the chemical contribution of ceria particles yields high removal rates even in neutral environments with low abrasive concentration. The interaction of ceria abrasives with an SiO₂ surface can be described by the general mechanisms of Cook as follows:

Cook [11] reviewed the glass polishing mechanism of CeO₂ abrasive. He proposed that an SiO₂ surface and CeO₂ particles would make a Ce-O-Si bonding, that Ce-O-Si(OH)₃ would be removed from the surface, and then the dissolution of Si(OH)₄ would follow. In addition, he stated that the chemically active particles will generate higher friction forces and higher surface stresses than more inert materials such as diamond, and proposed the “tooth” concept of CeO₂.

In ceria slurry, wherein an anionic organic additive such as poly-acrylic acid (PAA) is added, the “self-stopping” characteristic usually occurs due to the nonlinear relationship between the pressure and material removal rate, which can lead to more effective planarization through highly localized pressure on upper patterns than the silica-based slurry [3]. The dependency of material removal rate on pressure P and relative velocity V is defined by Preston’s equation in which the removal rate is linearly proportional to these two values [12]. However, many modifications of Preston’s equation have been developed to compensate for inaccuracies in the original equation from the late 1920s [13-16]. Today, the generalized form of Preston’s equation, which is widely accepted and used in the CMP process, can be written as follows:

$$RR = kP^\alpha V^\beta \quad (1)$$

where k is a constant and the values α and β are fitted parameters that vary depending on the process and the consumable set (i.e., pad and slurry) used. In particular, the exponent values can be an index not only to characterize the oxide CMP process, but also to correlate with the planarization of the oxide pattern.

As mentioned previously, silica-based slurry and ceria-based slurry have been widely used to planarize patterns of silicon dioxide as a dielectric material in the CMP process, but the fundamental studies done for understanding the material removal characteristics of the most attractive ceria-based slurry for STI CMP are not sufficient to effectively use the slurry in the CMP process. Thus, a comparative study between two types of slurry should be effective to experimentally analyze the planarization efficiency of ceria slurry

in this paper. Also, the monitoring of the friction force during oxide CMP was attempted in order to understand the material removal characteristics of ceria-based slurry. To understand the planarization efficiency of ceria-based slurry, material removal rate and friction force were investigated according to pressure and relative velocity. Then, nonlinear behavior of material removal rate, which can characterize the material removal characteristics of ceria-based slurry, was analyzed by using a non-Prestonian model of removal rate.

Experiments

Two types of slurries were used to investigate the planarization efficiency in STI CMP process. One, as standard, was fumed silica-based slurry with 12 wt% abrasive concentration in alkaline solution (pH 10.9), and the other was ceria-based slurry with 1.95 wt% abrasive concentration in neutral solution (pH 6.34). The slurry flow was kept constant at 150 cc/min. A polyurethane pad with micro pores (IC1400, Nitta-Haas) was used in all experiments. The pad was conditioned by using an ex situ method, either prior to or after the wafers had been polished. The conditions were a pressure of 60 g/cm² and rotational velocity of 60 rpm, using a diamond segment type conditioner.

Patterned Wafer Test

In order to analyze the planarization characteristics of ceria slurry, the first step of the STI CMP process was performed with the increase in polishing time at a pressure of 500 g/cm² and a rotational velocity of 60 rpm with carrier oscillation. An oxide patterned wafer of ~7000 Å thickness (SKW 3-2, SKW associates, Inc.) was used in this study, and the step height between the active oxide on Si₃N₄ and the field oxide on Si in the STI pattern was about 6000 Å. The planarization of the oxide patterned wafer was investigated in patterns of 100, 200, and 500 μm pitch with fixed 50% density using a reflectometer (ST5030-SL, made by K-Mac). During the CMP process, the unbalance in removal rate between active oxide and field oxide reflects the process of oxide planarization; therefore, the efficiency of planarization was defined as a function of the relative magnitude of field oxide removal to active oxide removal as shown in Equation (2) [17].

$$\text{Planarization Efficiency} = 1 - \frac{\text{Field Oxide Removal}}{\text{Active Oxide Removal}} \quad (2)$$

Polishing Test according to Pressure and Relative Velocity

To understand the effect of ceria abrasives on planarization efficiency, the 4 in thermal oxide wafers of 1 μm thickness were polished in the CMP equipment with the sensor (GNP POLI400, G&P Technology Inc.) so they could be used to monitor the friction force, according to pressure and velocity of process parameters. As shown in Figure 1, the monitoring method selected for this study was dynamic friction force measurement using a piezoelectric quartz sensor (Type 9135B, Kistler) at the back side of the polishing head, because of high accuracy, fast response time, and low interference. The force sensor had sensitivity of -3.8 pC/N and dynamic signal range of ~75 kHz. Table I describes the experimental conditions. The pressure ranged from 60-700 g/cm². The

rotational velocity of the carrier and platen ranged from 30-150 rpm, and the relative velocity, $v_{re} = rw$, can be calculated by multiplying of the distance r between the wafer-platen centers and the rotational velocity w .

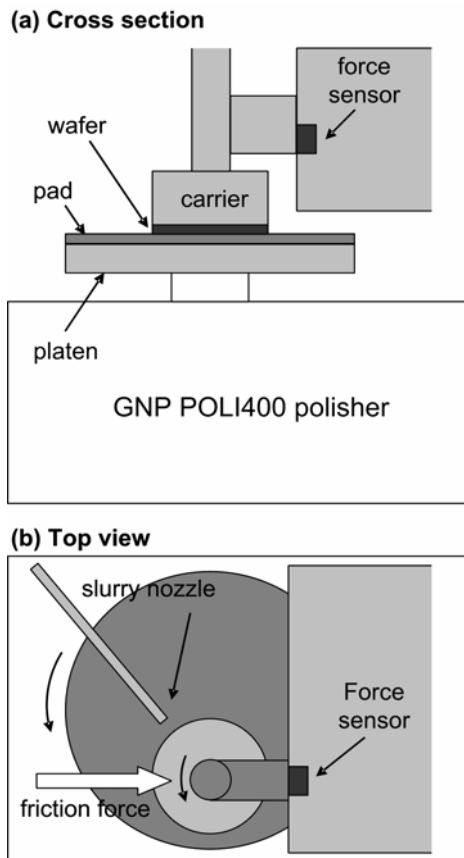


Figure 1. Schematic of CMP polisher with force sensor

TABLE I. Experimental Conditions

Parameters	Conditions
Pressure	60, 100, 300, 500, 700 g/cm ²
Rotational Velocity (carrier/platen)	30/30, 60/60, 90/90, 120/120, 150/150 rpm
Relative Velocity	22.1, 44.3, 66.4, 88.5, 110.7 m/min

Results and Discussions

Concept of Planarization Efficiency

Figure 2 shows planarization efficiency according to polishing time in the CMP using two slurries. The planarization efficiency using ceria-based slurry was better than that of silica-based slurry during polishing time below 120 s, regardless of the pitch size of oxide patterns. As polishing time increased from 120 up to 180 s, the planarization efficiency of two slurries became similar and steady. The results of the two slurries might be described as a nonlinear behavior of material removal rate as a function of pressure [3].

When the pad surface is in direct contact with oxide patterns during the CMP process, pad deformation can occur due to pattern geometry, as shown in Figure 3. Thus, the pressure p_1 on active oxide (i.e., the upper pattern) will be higher than the pressure p_2 on field oxide (i.e., the lower pattern). Also, a larger quantity of abrasive particles might be constrained on the upper pattern than on the lower pattern because of the difference in contact area between the patterns and pad asperities; this results in a higher friction force at the interface of the upper patterns. Therefore, the removal rate of active oxide will be higher than that of field oxide, and the planarization of oxide patterns can be achieved according to polishing time.

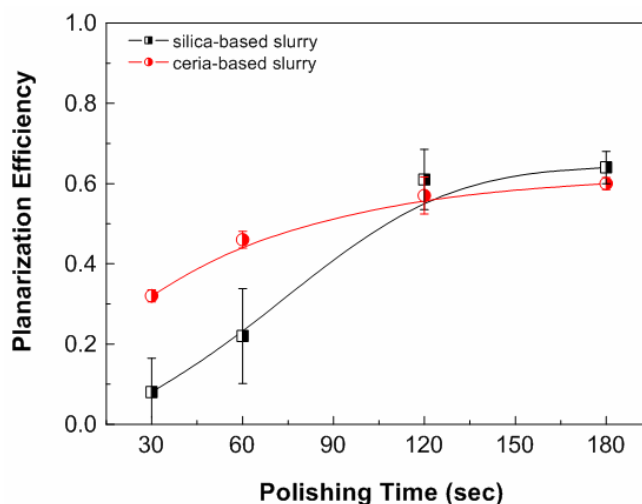


Figure 2. Planarization efficiency as a function of polishing time in STI CMP using silica-based slurry and ceria-based slurry

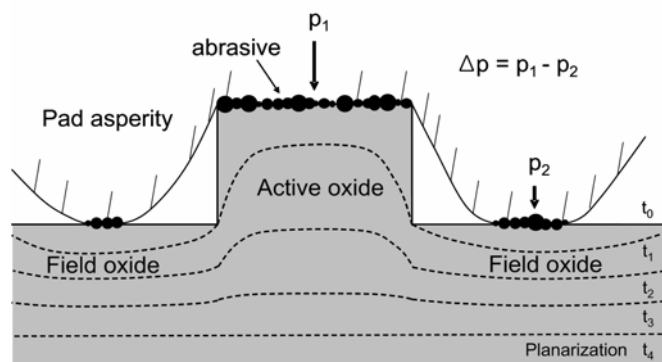


Figure 3. Schematic of planarization of oxide pattern according to polishing time

It is predicted that the nonlinear dependency of removal rate on pressure will be different between two slurries. Two slurries will have different exponent values in the main form of the modified Prestonian equation; i.e., $RR = kp^\alpha v^\beta$ [13-16]. Assuming that the removal rate is related to the p^α value at constant velocity, the removal rate according to pressure can be classified into three features based on increase of α values, as shown in Figure 4(a). In particular, the α value of ceria-based slurry should be higher than that of silica-based slurry in order to yield high planarization efficiency. If the removal rate of ceria-based slurry corresponds well with a feature at $\alpha > 1$, the change of

removal rate ΔRR between patterns will be high when the pressure change $\Delta p = p_1 - p_2$ between upper pattern and lower pattern is constant, as shown in Figure 4(b). Accordingly, the active oxide will be more rapidly removed by ceria abrasives according to polishing time than by silica abrasives, which results in better planarization efficiency from initial polishing time to the completion of the polishing step compared with the result using silica-based slurry.

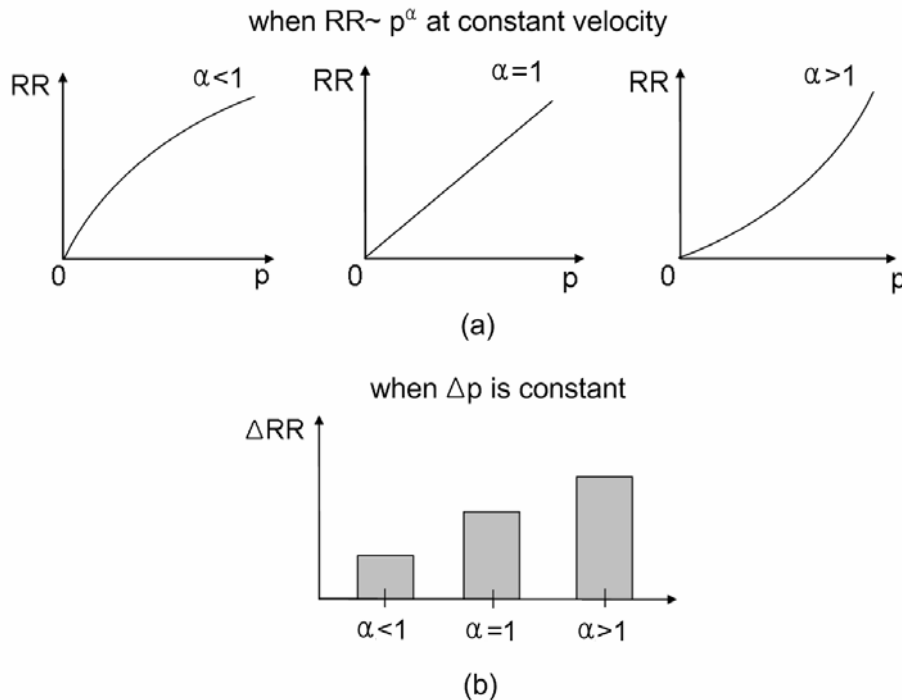


Figure 4. Schematic showing difference of removal rate between upper pattern and lower pattern according to exponent value of pressure; (a) removal rate as a function of pressure, and (b) change of removal rate between oxide patterns

Nonlinear Behavior of Material Removal Rate

Based on Equation (1) and experimental results using silica-based and ceria-based slurries, the nonlinear dependency of removal rate on pressure and relative velocity is summarized in Table II. The exponent values of each parameter were calculated using a least squares fit of the results of the removal rate. Also, the nonlinear dependency of friction force was added, with the assumption that the friction force is the power function of pressure and relative velocity; i.e., $F = k' P^a V^b$ [16].

The exponent values of each CMP process using two slurries were different from each other. As a result of the removal rate using silica-based slurry, the α and β values were 1.05 and 0.79, respectively. Thus, the removal rate was more nonlinearly dependent on the relative velocity than the pressure. The low exponent value of 0.79 indicates that the rate of increase in removal rate gradually saturates as a relative velocity increases (i.e., when $\beta < 1$). In contrast, the exponent values using ceria-based slurry were 2.06 and 0.98, respectively. Thus, the removal rate depended much more nonlinearly on the pressure. The high exponent value of 2.06 indicates that the rate of increase in removal rate rapidly increases as a pressure increases (i.e., when $\alpha > 1$), so it can yield high planarization

efficiency in the CMP process. The reason why the removal rate using two slurries is not a linear function of pressure and relative velocity seems to be that the contact condition between the wafer and pad changes according to the Sommerfeld number [18], which results in variation of friction force during CMP.

Therefore, the nonlinear dependency of friction force on pressure and relative velocity was also estimated. In the case of friction force, the a and b values using silica-based slurry were 0.81 and -0.03, respectively, and those using ceria-based slurry were 1.11 and -0.10, respectively. The rate of increase in friction force using silica-based slurry saturates as a pressure increases, whereas that using ceria-based slurry gradually increases. Also, the negative value of in the relative velocity exponent means that the friction force gradually decreases with the increase in relative velocity at the same condition of pressure, although the values of two slurries are very low.

TABLE II. Summary of fitted data of removal rate and friction force (numbers in parentheses are the reliability of data fitting)

	Silica-Based Slurry	Ceria-Based Slurry
Removal Rate	$RR = k_s P^{1.05} V^{0.79}$ (0.99)	$RR = k_c P^{2.06} V^{0.98}$ (0.97)
Friction Force	$F = k'_s P^{0.81} V^{-0.03}$ (0.97)	$F = k'_c P^{1.11} V^{-0.10}$ (0.99)

* The values of k_s , k_c , k'_s , and k'_c are $10^{-0.75}$, $10^{-3.78}$, $10^{-1.16}$ and $10^{-1.68}$, respectively. Also, the units of RR , F , P , and V are $\text{\AA}/\text{min}$, kg_f/cm^2 , and m/min , respectively.

Chemical Contribution of Ceria-Based Slurry

Based on these results, the concept of a chemical contribution can be proposed to characterize the effect of chemistry in removal processing of the two slurries. The chemical contribution can be expressed as follows:

$$\text{Chemical Contribution} = \frac{\text{Chemical Mechanical Removal}}{\text{Mechanical Energy Input}} = \frac{RR}{F \times V} \quad [3]$$

The rate of mechanical energy entering the CMP system can be defined as the product of the friction force F and relative velocity V . Also, the rate of material removal combined with the interaction between chemical and mechanical energy is expressed as the removal rate RR . Therefore, the ratio of the removal rate to the rate of mechanical energy can be index of chemical contribution in the CMP process, as shown in Equation (3).

When the power functions of removal rate and friction force in Table II were substituted into Equation (3), the results of silica-based and ceria-based slurries were $P^{0.24} V^{-0.18}$ and $P^{0.95} V^{0.08}$, respectively. The results showed that the chemical contribution of the two slurries is affected more by pressure than by relative velocity. The reason might be because friction heat increases with increase in pressure, which can lead to an increase in chemical activity in the slurry. However, the velocity also increases the temperature during CMP. Thus, the main source for more dependency of the chemical contribution on pressure can be the chemical reaction, which is induced by the wear behavior of abrasives such as two-body and three-body abrasion with indenting and plowing.

In particular, the chemical contribution of ceria-based slurry increases significantly with pressure in proportion to $P^{0.95}$. The chemical removal of oxide film in ceria-based

slurry will be very low because of the neutral environment in slurry. Nevertheless, the chemical contribution of ceria-based slurry is more dependent on the pressure than that of alkaline silica-based slurry. This might result from strong chemical interaction of ceria abrasive with the SiO₂ film surface, and then a higher chemical contribution of ceria-based slurry could result in greater dependency of the removal rate on pressure, compared to that of silica-based slurry. Therefore, it is estimated that the planarization efficiency of ceria-based slurry was better than that of silica-based slurry in the first step of the STI CMP process based on the nonlinear behavior and chemical contribution of removal rate.

Conclusions

The attempt was made to investigate material removal characteristics of silica-based and ceria-based slurries with exponent values of pressure and relative velocity, based on a modified form of Preston's equation. The results showed that the CMP process using two slurries has its own exponent values of pressure and relative velocity, which lead to nonlinear behavior of the removal rate. The nonlinear behavior of ceria-based slurry was more strongly dependent on the pressure than was silica-based slurry. Also, the chemical contribution of removal rate in ceria-based slurry was strongly affected by pressure because of the strong chemical tooth effect of ceria abrasives. Thus, it is estimated that the results yield good planarization efficiency in the STI CMP process.

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