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Fundamental Properties of Chemical Mechanical Polishing for Copper Layer Assisted by Optical Radiation Pressure*

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This paper presents a corrective Cu-CMP (Chemical Mechanical Polishing) method for obtaining higher planarized surface by forming laser aggregation particles on recessed areas of uneven copper surface before polishing. At first, the component analysis and formation condition of aggregated particles were investigated, which is obtained by laser irradiation into the slurry on the copper surface. This result indicated that the aggregated marks were purely made of SiO_2 particles contained in slurry and the height of particle aggregation could be controlled by laser irradiation condition. Next, proposed planarization method for uneven surface of copper layer was attempted. As the polishing progressed, the height of aggregated marks was reduced. Then, it was confirmed that the aggregated marks play a role of masks, and no material removal at the bottom surface of recessed areas takes place during the polishing. This process made it possible to realize high planarity on copper surface.

***Key Words*:** Cu-CMP, Optical Radiation Pressure, SiO_2 Particle, Surface Planarization, Laser Assisted Polishing, Laser Trapping

1. Introduction

Although scaling down of VLSI's design rules has developed steadily as predicted by Moore's Law, this accompanied some issues such as interconnect delay after the generation of VLSI devices at 180 nm node using traditional materials of aluminum and SiO_2. The development of VLSI structure has been advanced in order to reduce interconnect resistances and capacities among interconnect layers. In the next-generation VLSI, low dielectric constant (low-k) material than conventional SiO_2 is adopted for the insulating material and copper instead of aluminum is adopted for interconnects material. Copper has lower resistivity and higher electromigration immunity compared with aluminum, thus it is possible to reduce delay of signal. However, copper interconnect requires damascene processes because copper cannot be easily plasma etched. In the damascene process, copper is deposited into an etched inter-layer dielectrics (ILD) trench pattern, typically by electroplating over barrier and seed layer. Chemical Mechanical Polishing (CMP) is then carried out to remove the excessive copper and barrier material from the surface of silicon wafer. Ideally, the polished copper should be perfectly flat; unfortunately, an important nonideality is that copper lines suffer from copper dishing and oxide erosion due to CMP.

This research aims to realize the planarization with the chemical mechanical polishing where the aggregated marks of fine particles in slurry are formed with the optical radiation pressure by irradiated laser beam, and to process selective material removal of convex area intentionally in small uneven areas on the VLSI's circuit pattern.

In this paper, at first, the component analysis and formation conditions of aggregated particles were

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investigated, which is obtained by laser irradiation into the slurry on the surface of a wafer coated by Cu film. Furthermore, corrective planarization method, which fills up the recessed area with laser aggregated particles and polishes the area as one surface, was proposed and attempted to obtain high planarity on simulated uneven surface which was shaped by FIB (Focused Ion Beam) machining on the surface of copper layer.

2. Laser Aggregated Particles by Optical Radiation Pressure

"Laser Trapping"(1) is a well-known phenomenon that captures dielectric particles with optical radiation pressures, which are larger in size than the wavelength of light. It is considered that changes in momentum of laser beam at reflection and refraction, provide the generation of forces, when the laser beam irradiates into particles.

On the other hand, with particles smaller than the wavelength, the scattering of light results in a different phenomenon from considering light as rays. Therefore, it cannot be treated as the generation of optical radiation pressure by the change in momentum of rays, but optical radiation pressure working on fine particles can be directly derived by Maxwell's equation. Takaya, et al.(2) concluded, as shown in Fig. 1, that fine particles receive a thrust force to the focal point of laser beam, in parallel to the light propagation, and form the aggregated marks on the focal point.

Generally, in colloidal solution, fine particles can keep stable state of dispersion with balanced forces caused by surface potential and van der Waals forces. At around the focal point, the forces induced by the optical radiation pressure are applied additionally. Fine particles are condensed and gathered on a wafer coated by Cu film to form the aggregated marks due to the effect of heat.

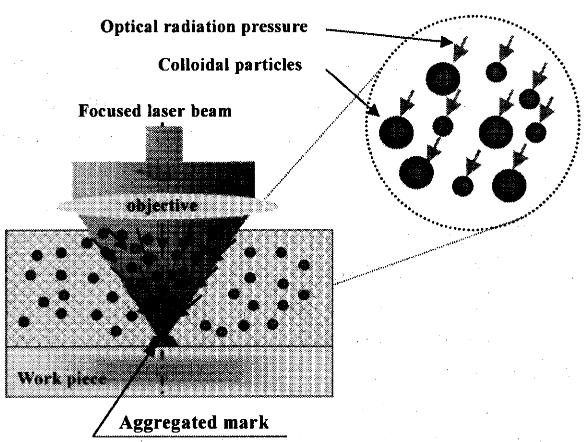

Fig. 1 Optical radiation pressure on fine particles

The experiment to form the aggregated marks is attempted with the experimental apparatus as illustrated in Fig. 2. Laser beam is emitted from the light source of Ar^+ laser (wave length: $\lambda=488$ nm) and irradiated into the test piece through objective lens (40 ×, NA=0.55). The test piece is diced silicon wafer coated by Cu film (10×10 mm) and is put on slide glass and filled with slurry. The slurry used in order to form aggregated marks is Rodel-Nitta ILD 1200 (major components: SiO_2, particle diameter: 140 nm, concentration: 3%). The test piece is set on the piezo XYZ stage. Positioning, focusing, and laser beam scanning motion are carried out by the XYZ stage, which can be positioned with Piezo actuators.

Figure 3 shows an example of the aggregated mark formed with the experimental apparatus. The width of the aggregated mark is approx. 5 μm and the height is approx. 2 μm.

3. Basic Concept of LAFP Method

In order to make planarization the uneven surface of copper layer, the removal of material in projected areas and the prevention of the removal to the bottom of the recessed parts are required simultaneously. Figure 4 shows the concept of the LAFP (Laser Aggregation, Filling-up & Polishing) method(3) that enables to fulfill these conditions.

Firstly, recessed areas on uneven copper layer

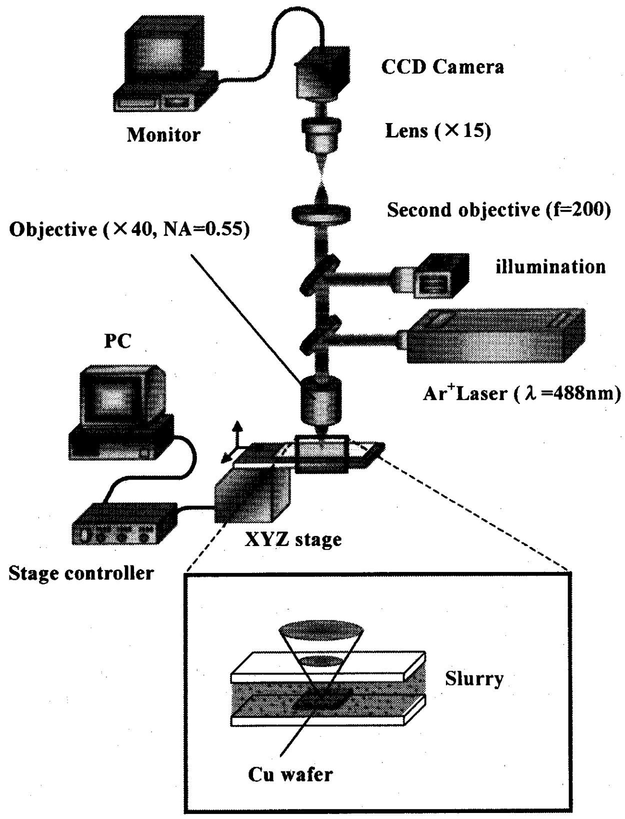

Fig. 2 The experimental apparatus for laser irradiation

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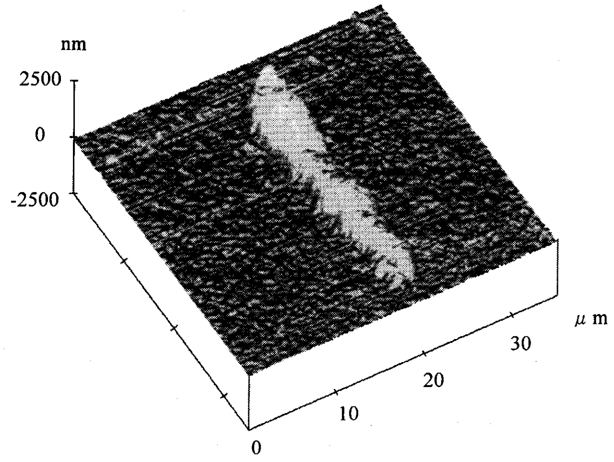

Fig. 3 Aggregated mark on copper surface by AFM observation

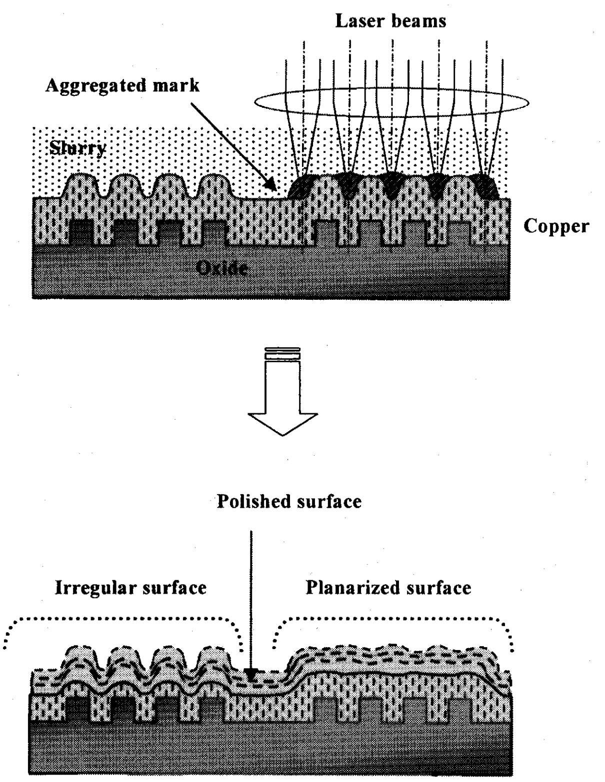

Fig. 4 Basic concept of LAFP method

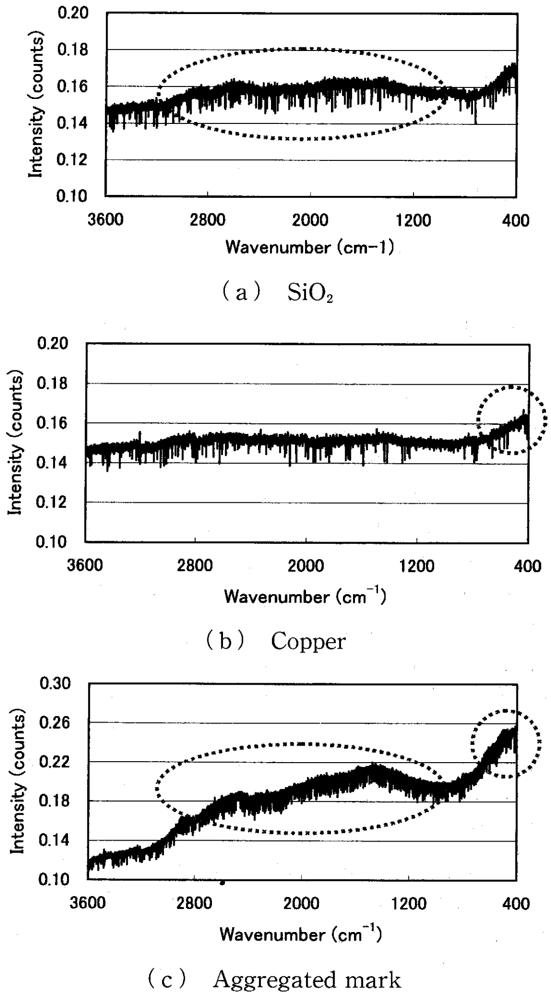

Fig. 5 Raman spectroscopy

surfaces are irradiated by laser beams for forming the aggregated marks, made of fine particles in slurry. In the next step, polishing is applied to that particular area. As a result of these processes, the aggregated marks of fine particles gradually collapse with the progress of polishing and the particles flow into the slurry again. Consequently, particle concentration is increased around the aggregated particles area and the removal of material is locally taken place. Then the bottom surfaces of recessed area are masked with aggregated particles, and no material removal at the bottom surfaces of recessed areas takes place during the polishing. Furthermore, the bottom surfaces of recessed areas is polished only when polished surface of copper layer reaches down to the bottom surfaces of trench. These properties show us a potential for polished surface with the higher level of planarity.

4. Analysis of Laser Aggregated Particles

The SiO_2 particles contained in slurry aggregating with laser irradiation on the copper surface was observed in Fig. 3, but it is not sure whether the observed aggregated mark is purely made of particles in slurry by AFM observation. The laser irradiation has the potential for impact on copper layer and smoothed copper layer could have been changed into convex shape by laser beam machining. Additionally, the components of the aggregated particles could have been chemically changed from original major components contained in slurry by the effect of heat of laser irradiation. The component of the aggregated mark has important implications in LAFP method because it is expected of function as abrasive grains. Consequently, the component of the aggregated mark was

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investigated by implementing two kinds of spectroscopy.

4.1 Raman Spectroscopy

We investigated the aggregated mark, Cu (copper layer) and SiO_2 (slide glass) in Raman Spectroscopy. Molecular structures can be clarified by the peak wavenumber of the spectrum and materials can be determined by the total waveform of the spectrum because Raman spectrum is characteristic of individual materials. Figure 5 shows Raman spectrum of these three kinds of materials. The broad peak wavenumber in the range of 1 200 to 2 800 cm^{-1} is shown by dotted circle in (a) SiO_2. This is characteristic of SiO_2, that is, silica particles. At the same time, broad peak wavenumber higher than (a) SiO_2 in the same range is shown by dotted circle in (c) Aggregated mark, this shows it has component of SiO_2 and tighter bond than silica particles in slurry because of thermal action of laser irradiation. The peak wavenumber centered on 400 cm^{-1} is characteristic of Cu, in fact, the peak wavenumber is shown by dotted in (b) Copper. The similar peak wavenumber shown by dotted circle in (c) Aggregated mark is caused by the component of copper layer under the aggregated mark.

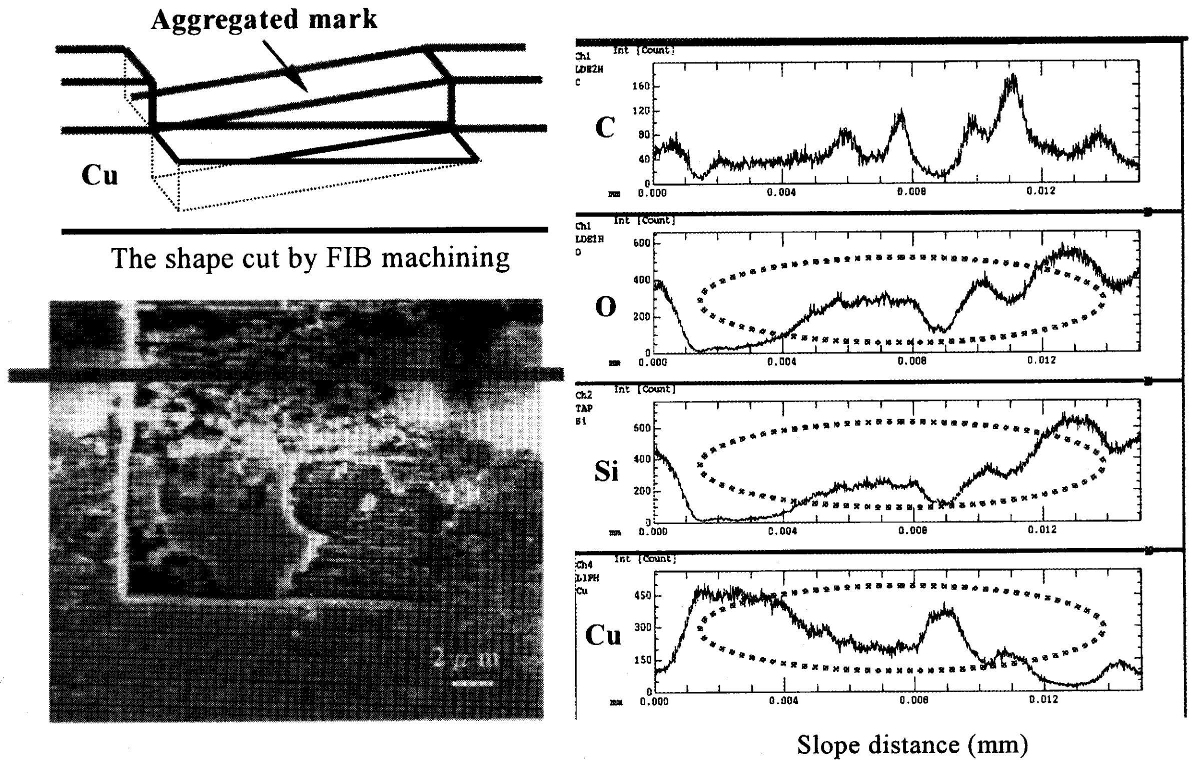
4.2 Auger Electron Spectroscopy

The aggregated marks gradually collapse during polishing process and particle concentration is locally increased around aggregated particles area. However, in order to act as abrasive grains, the aggregated mark must have the same component as abrasive grains (SiO_2) in the internal part of it. We investigated the internal component of the aggregated mark in Auger Electron Spectroscopy. Figure 6 (a) shows a part of the aggregated mark is obliquely cut and removed away by FIB (Focused Ion Beam) machining, in consequence, its internal part is exposed. The dotted circle in Fig. 6 (b) shows the component of both Si and O decrease along the slope of aggregated mark. As a result, internal part of the aggregated mark is also composed of both Si and O.

5. Preliminary Experiment

5.1 Control of Laser Aggregation

The dimension of aggregated mark should be easily controlled in order to make planarization any uneven surface. Figure 7 shows relations between laser power (mW), irradiation time (sec) and the height of aggregated mark. These aggregated marks examined in this section were formed by a single-motion of scanning the laser beam. The height of aggregated mark is proportional to both laser power and irradiation time. This result indicates that dimension of aggregated mark could be controlled by laser irradiation condition.



(a) Internal part of aggregated mark

(b) Analysis

Fig. 6 Auger electron spectroscopy

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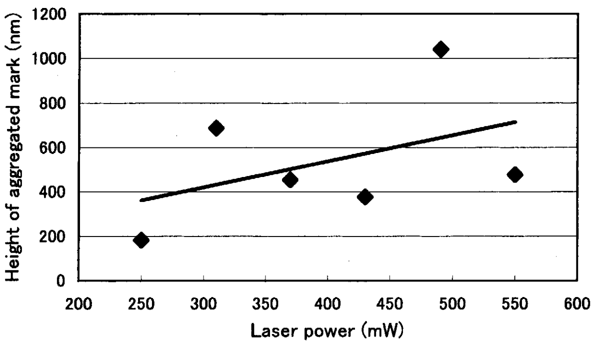
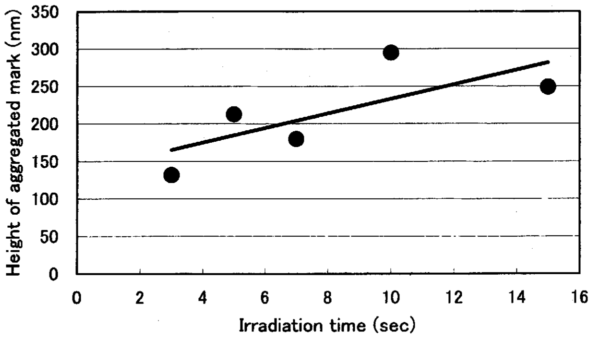


(a) Laser power



(b) Irradiation time

Fig. 7 Relation between the laser irradiation conditions and the height of aggregated mark

5.2 Polishing experiment

The polishing experiment was carried out to examine adhesion of the aggregated mark to the copper surface. The aggregated mark was automatically formed on the copper surface by scanning the laser beam many times. The scanning motions can be controlled by Piezo XYZ stage with function generator. Additionally, a water immersion objective (60×, NA=0.90) was used in order to form the accurate aggregated mark. The polishing experiments were implemented using the polishing unit illustrated in Fig. 8. The polishing unit consists of polishing head for rotation of the polishing pad and XY stage for traversing the test piece. The polishing pad with the size of ϕ10 mm attached to the polishing head is rotated at 180 rpm under applied pressure of 0.03 MPa controlled by air cylinder. While the test piece with the size of □10 mm is fixed on the vacuum chuck made from ceramics. The experimental conditions for forming the aggregated mark and polishing are shown in Table 1.

Figure 9 shows the averaged cross-sections of aggregated mark during polishing process. The dimension of aggregated mark formed on the cooper surface is approx. □18 μm and approx. 1.4 μm high before polishing. At T=9 min, the aggregated mark with approx. 38 nm in height was remained, but at T=14 min, aggregated mark was practically removed and the smoothed surface with 8.5 nm Rrms was obtained. It was confirmed that the aggregated mark of approx. 1.4 μm initial height would be removed from the copper surface at about T=14 min in this polishing condition.

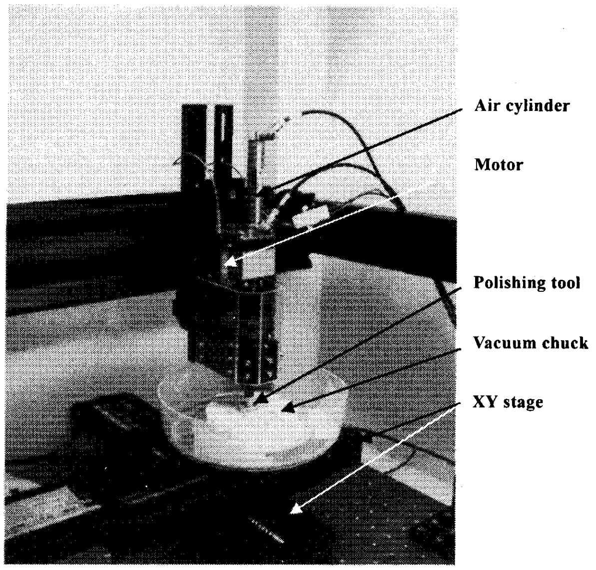


Fig. 8 Polishing unit for experiments

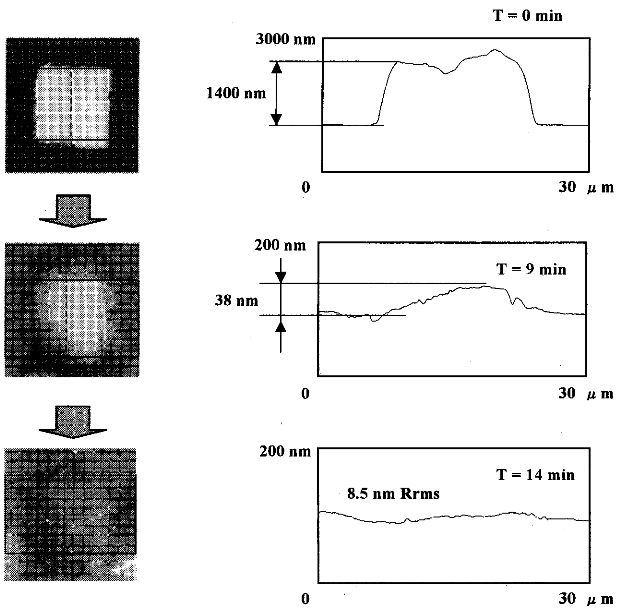


Fig. 9 Averaged cross sections of aggregated mark during polishing

6. Polishing Based on LAFP Method

Based on the LAFP concept, two kinds of polishing experiments were implemented. Two different test piece with recessed area or trenches were used for polishing experiments in order to discuss the effect of aggregated mark on planarizations of uneven surface. The experiments were implemented in the same condi-

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Table 1 Experimental conditions

Conditions for polishing	
Polishing equipment	Small tool polishing
Slurry	SiO_2 / PLANERLITE-7101 (Fujimi)
	Particle diameter : 35 nm
	Concentration : 5%
Rotation speed	180 rpm
Polishing pressure	0.03 MPa
Polishing pad	IC 1000
Velocity of XY stage	40 mm/min
Conditions for forming aggregated marks	
objective	Water immersion objective (60×, NA=0.90)
Laser power	190 mW (§5.2) 170mW (§6)
Scan rate	16 μm/sec

tions as section 5.2, shown in Table 1 (*notice*: only for laser power in forming the aggregated mark was arranged lower than section 5.2).

6.1 Polishing experiment for dishing

As previously stated in section 1, the polished copper lines are not perfectly flat but suffer from copper dishing due to CMP process. This experiment was implemented in order to improve copper dishing. Two recessed areas were shaped on the surface of test piece of diced wafer coated by Cu film by FIB (Focused Ion Beam) machining. One recessed area was directly polished, and the other was polished after aggregated mark was formed at the bottom surface of the recessed area.

The size of recessed area shaped on the test piece is approx. □ 20 μm, and approx. 80 nm deep. Figure 10 shows the changes in the averaged cross-sections all over the recessed area during polishing process. The depth of recessed area has a tendency to reduce with the progress of polishing time, but at even $T=19$ min, the recessed geometry is still remained. Since the polishing rate of the top surface of recessed area is a little faster than that of the bottom surface of recessed area at the beginning of polishing process, polishing makes slow progress in planarization. However, when the difference between top and bottom surface of the recessed area becomes smaller to be approx. 25 nm at $T=14$ min, the both surfaces are considered to be polished at almost the same rate due to uniformly applied pressure all over the surface. For this reason, the recessed area was not perfectly eliminated. The fact that recessed geometry with approx. 25 nm deep was finally remained indicates limits on the planarization using conventional CMP process.

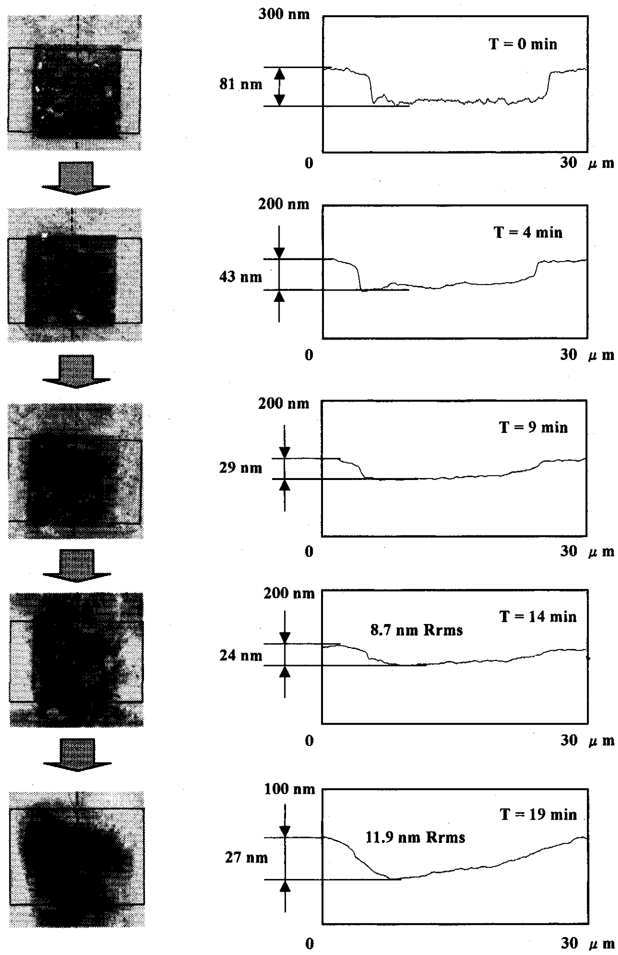

Fig. 10 Averaged cross sections of recessed area without aggregated mark during polishing

The averaged cross-sections of the recessed area with aggregated mark during polishing process are shown in Fig. 11. The aggregated mark was formed at the bottom surface of the recessed area, and the height of aggregated mark is approx. 950 nm before polishing. The height of aggregated mark is gradually reduced with the progress of polishing time, and at $T=9$ min, the convex aggregated mark is almost removed from the copper surface, which means the surface of recessed area filled up by aggregated particles is identical plane with the polished copper surface. After $T=9$ min, the entire area is seen to be uniformly polished. The fact suggests that laser aggregated particles play a role of masks in polishing process and no material removal at the bottom surface of recessed area would probably proceed. At $T=14$ min, most of aggregated mark would be removed at the bottom surface, and aggregated mark would be removed from cooper surface at $T=19$ min considering the result of section 5.2 (see Fig. 9). The smoothed and planarized surface with 4.8 nm Rrms in the

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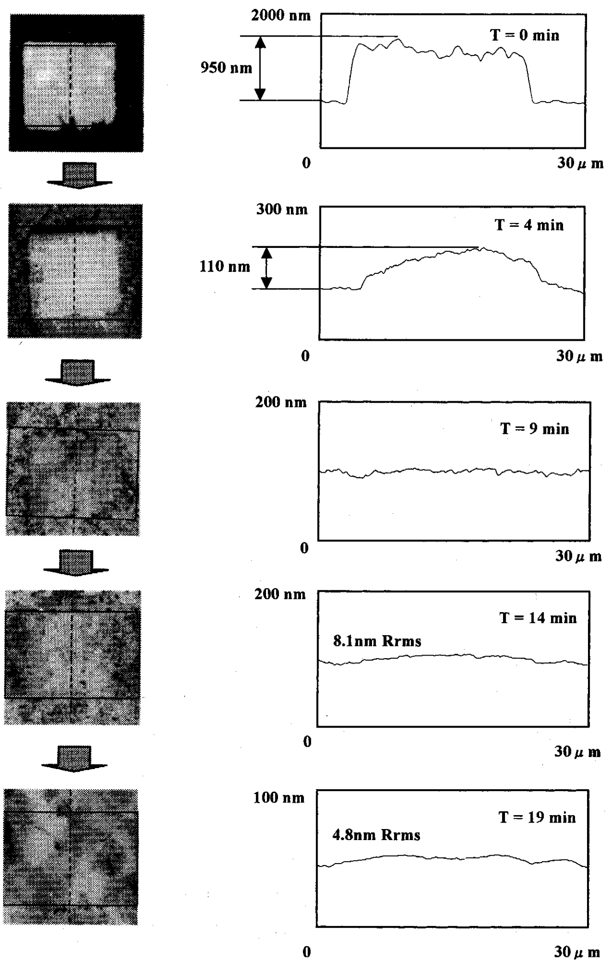

Fig. 11 Averaged cross sections of recessed area with aggregated mark during polishing

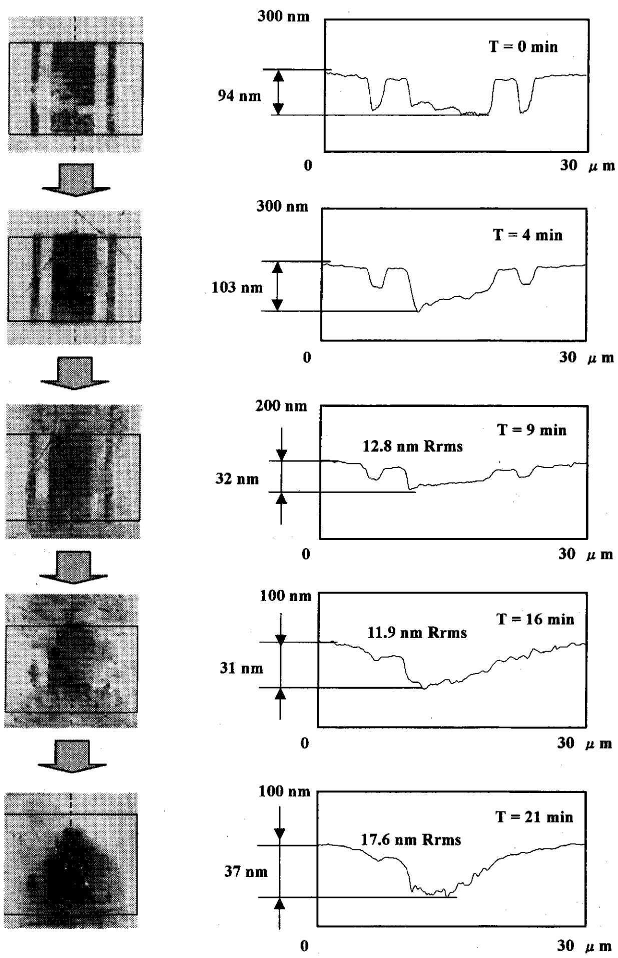

Fig. 12 Averaged cross sections of trenches without aggregated mark during polishing

entire area was obtained at $T=19$ min, at which the polished surface could reach the bottom surface of recessed area. This result indicates that our proposed LAFP method is effective technique for planarization of copper layer.

6.2 Polishing for random trenches

Two random trenches were shaped on the surface of test piece of diced Cu wafer by FIB machining. As with section 6.1, one random trench was directly polished, and the other was polished after aggregated marks were formed at the bottom surface of trenches.

Figure 12 shows the changes in the averaged cross-sections of trenches during polishing process. The width of central trench is approx. 10 μm, that of trenches of both sides is approx. 2 μm, and the depth of these trenches is approx. 94 nm at the maximum before polishing. Trenches of both sides gradually are eliminated as the progress of polishing time, and at $T=16$ min, the entire area of trenches turns into almost concave shape after trenches of both sides were together with the central trench. Finally, the recessed geometry with approx. 35 nm deep is remained as a recessed area.

The averaged cross-sections of the trenches with aggregated marks during polishing process are shown in Fig. 13. The aggregated marks are formed at the bottom surfaces of trenches, and the height of aggregated mark is approx. 905 nm before polishing. Although the smoothed and planarized surface was achieved compared with the trenches directly polished by similar removal process to the recessed area with aggregated particles (see section 6.1), aggregated mark may be still remained at $T=21$ min from the observation of 13 nm step. In near future, we need to exactly examine whether the aggregated mark is actually removed or not in order to finally achieve the planarized surface.

7. Conclusion

A corrective planarization method for copper surface, which is based on the particles aggregation phenomena by the optical radiation pressure, was attempted by experiments and proposed. Consequently, four conclusions were obtained as follows;

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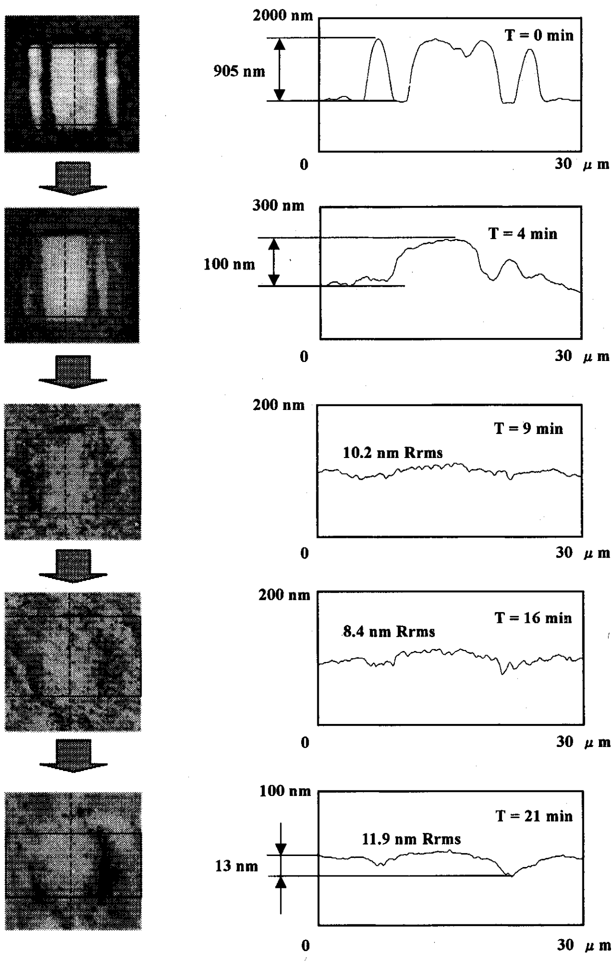

Fig. 13 Averaged cross sections of trenches with aggregated marks during polishing

(1) The phenomenon of particles aggregating on copper layer surface by using optical radiation pressure was observed.

(2) It was confirmed that laser aggregated particles is purely composed of silica particles contained in the slurry and has tighter bond than silica particles.

(3) It was suggested that the dimension of the aggregated mark could be controlled by laser irradiation conditions, such as laser power and irradiation time.

(4) After aggregated marks are formed and filled up at the bottom surface of the recessed areas on a wafer coated by Cu film, polishing is carried out. This process makes it possible to realize high planarity on copper surface.

As a final result, the smoothed and planarized surface is achieved with LAFP (Laser Aggregation, Filling-up & Polishing) method, and the method has a high potential for planarization.

Acknowledgment

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