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

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Summary
With the proposed Cu-CMP (Chemical Mechanical Polishing) method, laser beam is irradiated into the slurry on the silicon wafer coated with blanket copper layer. Moreover, after the fine particles in slurry are aggregated on the surface of the Cu wafer with optical radiation pressure, the polishing process is implemented. This paper describes about the result of an experiment of laser irradiation into the slurry on the Cu wafer. The phenomenon of SiO2 particles aggregating with laser irradiation was observed, and conditions to create particle aggregation were investigated. This result indicated that the height of particle aggregation could be controlled by irradiation laser power. Furthermore, the properties of laser aggregation particles on copper layer were also examined. This gives that the aggregated mark closely contacts copper layer.

Keywords: Cu-CMP, optical radiation pressure, SiO2 particle, surface planarization

1. Introduction
Scaling down of VLSI's design rules has developed steadily as predicted by Moore's Law, and interconnect delay drastically increases after the generation VLSI devices at 180nm using traditionally material of aluminum/SiO2. The copper/low-k materials processes have been started to build the VLSI structure for improving the calculation speed and for preventing increases in resistances and capacities among interconnection layers. Interconnect delay is reduced because copper is lower resistivity and higher electromigration immunity compared with aluminum. However, Copper cannot be easily plasma etched, thus copper metallization requires a damascene process. In the damascene process, copper is deposited into an etched inter-level dielectric (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 outside the desired lines. 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.

In this study, we have proposed a corrective Cu-CMP method using optical radiation pressure in order to achieve high-precision surface planarization. With the proposed Cu-CMP method, laser beam is irradiated into the slurry on the Cu wafer. The particles in the slurry are trapped by the optical radiation pressure and aggregated on copper layer surface. By filling up a specific area with aggregated particles by laser irradiation, we can control particle concentration in the slurry, consequently, polishing rate is accelerated around the aggregated particles area. Laser aggregation particles also play a mask role in polishing process, no material removal at the bottom surface with itself take place during the polishing. Furthermore, the bottom surface with laser aggregation particles is polished only when polished surface reaches down to the bottom surface of copper layer. These properties show us a potential for polished surface with the higher level of planarity.

2. Laser particles aggregation by optical radiation pressure
"Laser Trapping" 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. concluded, as shown in Fig1, 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 Cu wafer to form the aggregated marks due to the effect of heat.

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 ($\lambda = 488$nm) and irradiated into the test piece through objective lens (40 ×, NA=0.55). The test piece is diced silicon wafer coated with blanket copper layer (10 × 10mm) and is put on slide glass and filled with slurry. The piece is set on the piezo XYZ stage. Positioning, focusing, and laser beam scanning motion are carried out by the XYZ stage.

Fig.3 shows an example of the aggregated mark created with the experimental apparatus. The phenomenon of SiO$_2$ particles aggregating with laser irradiation on the copper layer was observed. The width of the aggregated mark is approx. 5 $\mu$m and the height is approx. 2 $\mu$m.

![Fig.1 Optical radiation pressure on fine particles](image1)

![Fig.2 The experimental apparatus for laser irradiation](image2)

![Fig.3 Aggregated mark on Cu wafer by AFM observation](image3)

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. Fig.4 shows the concept of the LAFP (Laser Aggregation, Filling-up & Polishing) method$^1$ that enables to fulfill these conditions.

Firstly, dimples on uneven copper layer surfaces are irradiated by laser beams for building 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 mark gradually crumbles, particle concentration increases and polishing rate is accelerated around itself. Then, the aggregated mark also play a mask role in polishing process, no material removal at the bottom surface of recessed areas takes place during the polishing. Furthermore, the bottom surface of recessed areas is polished only when polished surface of copper layer reaches down to the bottom surface of trench. These
properties show us a potential for polished surface with the higher level of planarity.

4. Analysis of laser particles aggregation

The phenomenon of SiO₂ particles aggregating with laser irradiation on the copper layer was observed in Fig.3, but it cannot be determined by AFM observation if the observed aggregated mark is purely made of particles in slurry.

By laser irradiation, the aggregated mark could have been composed of copper or particles component of the aggregated mark might be chemically changed from original particles component, SiO₂. 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 investigated by implementing two kinds of spectroscopy.

4.1 Raman Spectroscopy

We investigated the aggregated mark, Cu (copper layer) and SiO₂ (slide glass) in Raman Spectroscopy. Fig.4 shows Raman spectrum of these three kinds of materials. Broad peak in the range of 1200 to 2800 cm⁻¹ is shown by dotted circle in (a)SiO₂. This is characteristic of SiO₂, that is, silica particles. At the same time, broad peak higher than SiO₂ in the same range is shown in (b)Aggregated mark, this shows it has component of SiO₂ and tighter bond than silica particles in slurry because of thermal action of laser irradiation. A peak centered on 400 cm⁻¹ is caused by copper layer under the aggregated mark, in fact, the same peak is shown in (c)Copper.

4.2 Auger Electron Spectroscopy

The aggregated mark gradually crumbles and rumbles, as a result of this, particle concentration increases around itself. However, in order to act as abrasive grains, the aggregated mark must have same component as abrasive grains (SiO₂) even in the internal parts. We investigated the internal component of the aggregated mark in Auger Electron Spectroscopy. Fig.5(a) shows a part of the aggregated mark is obliquely cut and removed away by FIB (Focused Ion Beam) machining. Then its internal part is exposed. The component of Si, O on the inside decreasing along with slope is shown by dotted circle in Fig.5(b). As a result of this, internal part of the aggregated mark is also composed of Si, O.

4.3 Polishing experiment

In LAFP method, the aggregated mark is considered to contact copper layer closely if it is still left on the copper layer in polishing. By carrying out polishing experiment, we investigated how the aggregated mark closely contacts copper layer. Firstly, four aggregated marks on copper layer along the scanning locus of the laser beam are formed. In the next step, the test piece is polished for 8min. Fig.6 shows the changes in its cross-section during polishing. At T=8min, the aggregated marks still left on copper layer is observed. This gives that the aggregated marks are not easily removed away in polishing process.

5. Fundamental experiment

5.1 Control of laser aggregation

The scale of the aggregated mark should be easily controlled in order to make planarization any uneven surface. Fig.7 shows relations between the height of the aggregated mark and laser power, irradiation time(sec). The height of the aggregated mark is proportional to both the laser power and irradiation time. This result indicates that the scale of the aggregated mark could be controlled by laser irradiation condition.
5.2 Laser aggregation on uneven surface

In LAFP method, the aggregated marks must be formed on dimples of uneven copper layer. In order to make sure of phenomenon of particles aggregation on dimples, firstly trenches with 250 nm deep and 2 μm wide are shaped on the copper layer surface by FIB machining. In the next step, the fundamental experiment aggregating the SiO₂ particles along the trench is performed. Consequently, as shown in Fig.8, the aggregated mark with about 260 nm high is observed. This fast suggests that the phenomenon of particles aggregation takes place even on the dimples of uneven copper layer surface.

6. Conclusions

A corrective planarization method for copper layer, which is based on the particles aggregation phenomena by the optical radiation pressure, was proposed. The results obtained in this paper are as follows;
(1) The phenomenon of particles aggregating on copper layer surface by using optical radiation pressure was observed.
(2) It was confirmed that laser particles aggregation is purely composed of silica particles in the slurry and has tighter bond than those.
(3) It was suggested that the scale of the aggregated mark could be controlled by laser irradiation conditions, such as laser power and irradiation time.

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