Laser Planarization Process Assisted by Chemical Mechanical Polishing for Copper Surface

Yasuhiro TAKAYA1, Keiichi KIMURA2, Takashi MIYOSHI1, Toshiki MIYAMOTO1, Keisuke SUZUKI3

1 Osaka University, 2-1 Yamaadoka, Suita, Osaka, 565-0871 JAPAN
2 Kyushu Institute of Technology, 680-4, Kawazu, Itaku, Fukuoka, 820-8502 JAPAN
3 Rodel Nitta Company, 6-5-6, Sakyo, Nara-shi, Nara, 631-0801 JAPAN

1. INTRODUCTION
ULSI have been developed constantly followed by Moore’s law [1], and improvement of ULSI’s performances and supply with low price have made ULSI spread over every human activities and every people’s life on foundations. This evolution was realized by ULSI process innovation in respect of lithography and planarization process for multi-layers interconnects. Particularly, in planarization process, planarization technique has been advanced by development of CMP (Chemical Mechanical Polishing) technique [2] and by application for planarization process in ULSI manufacturing process. In recent years, CMP technology encountered turning for new direction such as planarization for new material of Cu interconnects and Low-k dielectrics, and Cu Dual-Damascene process which is based on CMP technology is introduced. However, some difficulties as Cu layer delaminating and damages generation on Low-k films [3] are coming up seriously in the process. Low down force and high rotation speed CMP machine [4] was developed to solve these problems, but performances are not sufficient yet. As an essential solution for the problem, material removal with no contact between a polishing pad and a surface of silicon wafer is one of the basic ideas. Based on the idea, ECMP (Electro chemical mechanical planarization) [5] has been tried, but geometrical selectivity for planarization is insufficient because of its properties of material removal mechanism, and further, material removal speed is necessary for increasing.

On the research, the new material removal method is attempted for a development of no-contact planarization process with high geometrical selectivity on Cu film’s asperity. On this method, laser light irradiates onto the surface of Cu film on the silicon wafer in reactive liquid environments. Material removal with the depth of nanometer order can be obtained by localized activation of laser-material interaction or laser-induced chemical reaction at just the microscopic region where tightly focused laser light irradiates. As a first step of the research, the fundamental experiments were carried out and possibilities to control material removal rate are investigated.

2. LASER PLANARIZATION PROCESS
We propose the new laser planarization method that is based on the control of local material removal process using laser-material interactions. The process is performed without using a polishing pad to avoid the serious problems such as dishing, erosion and delaminating on copper layer and inter-layer dielectrics (ILD), as seen in the conventional CMP technologies with using a polishing pad.

Fig.1 shows the basic concept of the laser planarization process. Copper interconnect requires damascene processes because copper cannot be easily plasma etched. In the damascene process, copper is deposited into an etched ILD trench pattern, typically by electroplating over barrier and seed layer. Then the excessive copper should be removed and the copper film’s asperity is finished to be perfectly flat ideally. In the laser planarization process, copper surface is irradiated by tightly focused laser light in reactive liquid environment such as slurry used for CMP. The planarization process is performed by scanning the laser light in the radial direction on copper surface of a rotating wafer as shown
in Fig.1 (a). Depending on a fluence, material removal is considered to be occurred by laser-material interactions in reactive liquid environment such as laser-induced evaporation, laser-induced wet chemical etching, laser ablation or a combination of them. So, it is expected that the material removal rate can be controlled by changing the laser irradiating conditions, and moreover the control is localized in the laser spot size. As the initial phase of the laser planarization process, rough removal process with constant rate in depth is needed to decrease the excessive copper quickly. In this process, large constant fluence is employed to remove copper with high rate as indicated in Fig.1 (b). However most of the excessive copper is eliminated by this process, there exists irregularities such as the humps on the deposited copper layer, which reflects the trench patterns. At this phase, selective removal process is required to remove the humps. In this process, removal rate for each hump, which can be estimated from the trench patterns, is controlled by modulating fluence as indicated in Fig.1 (c). Therefore, the laser planarization method makes it possible to attain no-contact planarization of copper film’s asperity with high geometrical selectivity.

3. EXPERIMENTAL SETUP

Schematic diagram of the optical system is illustrated in Fig.2 (a). The optical system is composed of a microscopic optical system and a laser irradiation optical system for controlling the laser light illumination conditions such as beam spot position, scanning frequency and laser power. The light with wavelength of 488 nm is emitted from a Ar+ laser and is deflected by a pair of computer-controlled galvano-mirrors with axes perpendicular to each other for scanning the beam.

The laser beam is deflected by a beam splitter, after through a pair of relay lens unit to adjust maximum scan length within the aperture size of an objective, then focused by a water immersion objective with N.A. of 0.9. The focused laser spot of about 0.35 μm (theoretical) in diameter is scanned on a copper surface of a workpiece which consists of Cu layer with 1000 nm thickness, Cu seed layer with 100 nm, TaN barrier layer with 50 nm and silicon substrate as shown in Fig.2 (b). The workpiece is dipped in the Cu-CMP slurry containing copper etchant. Positioning of the workpiece is performed using a xyz-stage with positioning accuracy of 5 nm, which is driven using PZT actuators. The experimental conditions are listed in Table 1.

4. FUNDAMENTAL EXPERIMENT

In order to investigate the material removal properties in working fluid and in the laser irradiation conditions as process control parameters, fundamental experiments to produce fine grooves on a copper surface. The tightly focused laser beam is scanned repeatedly on the surface with the scan speed of 56 μm/sec and scan rate of 1 Hz. Veeco NanoScope IIIa AFM is used to examine the processed surface in detail.
4.1 Material removal properties

Machining of a fine groove on a copper surface for two types of working fluids is performed to investigate material removal property for the process in a reactive liquid environment and in not reactive. Fig.3 shows the difference in material removal property for each working fluid. The copper surfaces were treated at the laser scan number of 600 times in linear motion for a range of laser power and analyzed by AFM. According to the AFM observations shown in Fig.3 (a), the grooves produced for ultra-pure water become unacceptable from the point of view of controlled material removal. At the laser power of 144 mW, a small amount of sputtered debris appeared around the extremely discontinuous groove. The groove edge is not clearly recognizable and irregular. At 198 mW, remarkable ejected debris was present possibly due to the melted material being pushed to the sides of the deep groove or vaporization of the removed material. The depth and the width of the groove are not measurable. On the other hand, material removal property for Cu-CMP slurry is drastically different from that for ultra-pure water. Fig.3 (b) shows the AFM images of the grooves produced for Cu-CMP slurry and examples of the cross sections. At both 144 mW and 198 mW, not only was the fine groove with smooth and sharp edge produced, but ejected and sputtered debris did not appear around the groove. According to the cross sections, the grooves are confirmed to be V-shape. The groove produced at the laser power of 198 mW is deeper than 144 mW, but both of the grooves have almost same width. Depth of a produced groove in Cu-CMP slurry is found to be related to irradiated laser power.

4.2 Laser power and material removal rate

In order to examine the relationship between laser power and material removal rate, machining of the grooves for Cu-CMP slurry was achieved over a range of laser scan number for each laser power. Depth and width of the grooves are estimated by the cross sections obtained from the AFM images.

Fig.4 shows the relationship between the depth of the produced groove and the laser scan number for each laser power. At the laser power of 198 mW, the depth of about 250 nm to 800 nm is directly proportional to the laser scan number of about 300 to 1200 times. The depth changing from several nm to nearly 100 nm at 36 mW shows almost same tendency as 198 mW for the laser scan number up to 2500 times. But the depth ranging from several nm to about 400 nm shows different change at the laser power of 72 mW, 108 mW and 144 mW. The linearity of the depth and the laser scan number is not approved from the
depth more than 60 nm.

Fig. 5 shows the relationship between the width of the produced groove and the laser scan number for each laser power. Although the measurement results show fluctuation between nearly 1.5 μm to 2.5 μm, the width is independent of laser scan number and laser power. Consequently, material removal rate in depth is potentially controllable by laser power and scan number, but not in width.

4.3 Results and Discussion

Controllability of material removal in depth is considered from the point of view of material removal rate per one laser scan for laser irradiation power. Fig. 6 shows the material removal rate per one laser scan in depth for each laser power. The material removal rate is almost directly proportional to the laser power ranging from 36 to 144 mW for the depth less than about 60 nm, but rapidly jumps to 0.7 nm/scan at the laser power of 198 mW for the depth more than about 200 nm. Since material removal rate is supposed to linearly change with laser power, a copper layer in Cu-CMP slurry is assumed not to be bulky structure with uniform material but covered with a thin film of different material. The thickness of the thin film can be estimated nearly 60 nm. Taking account of reactive liquid environment of Cu-CMP slurry, the experimental results suggest the material removal process model as shown in Fig. 7. Being covered in oxide film by the oxidizer included in Cu-CMP slurry where the copper surface is suitable, it becomes the passive state. It is supposed that the material removal rate of this Cu passive state film for laser irradiation is lower than that of Cu. Because the Cu passive state film is removed initially for low laser power the material removal rate is low as suggested in Fig. 7 (a). Reaching at Cu layer, the material removal rate increases suddenly as shown in Fig. 4. When Cu passive state film is irradiated by high power laser, the depth of removed material reaches into Cu layer in an instant. The Cu layer irradiated by high power laser is dug much deeper as indicated in Fig. 7 (b). Meanwhile, since Cu passive state film is not generated significantly in ultra pure water, the uncontrollable material removal properties shown in Fig. 3 result from the different material removal process of direct laser-copper interaction.

5. CONCLUSIONS

The new laser planarization method which is based on the control of local material removal process using laser-material interactions are proposed. Using Cu-CMP slurry, the fine groove with smooth and sharp edge produced without ejected and sputtered debris. Considering material removal rate per one laser scan for laser irradiation power, the material removal process model is suggested. The experimental results can be explained by the assumption that the material removal rate of this Cu passive state film for laser irradiation is lower than that of Cu. Nanometer order material removal rate in depth is potentially controllable by laser power and scan number.

REFERENCES