Optimization of brush scrubbing condition on Cu/low-k damascene structure by using pressure sensing sheet

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Abstract The optimum condition of brush scrubbing for Cu/low-k dielectric damascene structure was explored by using the pressure sensing sheet. Damage introduction during brush scrubbing after chemical mechanical planarization is one of major issue for LSI interconnect fabrication. The pressure sensing sheet has been investigated for a measurement of dynamic pressure variation during planarization by authors. In order to reduce damage introduction to low-k dielectric during brush scrubbing with satisfaction of particle removal efficiency, a tribological study of brush contact on a wafer was carried out. High speed brush rotation with low down pressure condition suppressed a variation of electric characteristics, such as dielectric constant and leakage current, and scratches with enough particle removal. The hydrodynamic flow of cleaning chemicals by brush rotation was revealed to increase particle drag force by dynamic measurement with the pressure sensing sheet and high speed camera. The pressure sensing sheet is considered to be a very effective method to optimize the brush scrubbing process.

1. Introduction

Brush scrubbing for wafer cleaning has been commonly adapted in semiconductor fabrication process and this process has also applied as a cleaning technique to wafer surface containing a large number of adsorbed particles and slurries after chemical mechanical planarization (CMP). A shear force generated by a friction between brush surface and the wafer in brush scrubbing is considered to be necessary to remove adsorbed particles and residue slurries after CMP by a contribution of drag force to the absorbed particles and residue slurries after CMP. Increase in down force is usually used to obtain high shear force in brush scrubbing. It is, however, very important to adjust a shear force value, because while low shear force is not significant to remove particles embedded on the wafer surface, an excess one leads to scratch creation and/or electrical properties degradation. In this study, a tribological study of brush scrubbing in post CMP cleaning of an ultra low-k dielectric is carried out. The optimum brush scrubbing condition is obtained by measuring the shear force between brush and wafer and by an observation of a dynamic contacting behavior of brush to wafer by the pressure sensing sheet. Then the optimum brush scrubbing condition was validated by evaluations of particle removal, scratch formation and degradation of electrical properties at various combinations of the brush rotation rate on the ultra low-k film.

2. Experimental

Two types of substrates were prepared in this study. A 100 nm-thick Cu film on a 30 nm-thick tantalum nitride (TiN) film was deposited on a 200 mm diameter silicon substrate by physical vapor deposition for a measurement of shear force. After some of Cu on TiN films were dipped into TiN CMP slurry solution produced by the Hitachi Chemical Co., Ltd., to absorb slurry residues, brush scrubbing was carried out to figure out particle removal efficiency. A 100 nm-thick fluorocarbon film was also prepared on a 200 mm diameter silicon substrate by the radial line slot antenna plasma enhanced chemical vapor deposition using a mixture of C5F8 and Ar gases [1]. Scratch formation and variation of electrical properties were evaluated on these substrates.

A brush scrubbing equipment with the brush and wafer rotation mechanism was used. A loadcell placed between a wafer holder and fixed plate is able to measure shear force generated by friction between brush and wafer. The down pressures are varied from 5.5 kPa to 6.9 kPa, and the brush rotation rates are set from 50 rpm to 500 rpm at a fixed 150 rpm wafer rotation rate. A citric acid with additives is used as a cleaning solution [2]. Number of residue slurries down to 0.16 μm size after cleaning was counted by the KLA-Tencor Surfscan 6420. Atomic force microscope (AFM) was used to observe scratch generation after brush scrubbing. Leakage current densities and dielectric constants of the fluorocarbon films before and after brush cleaning were measured by the mercury probe with a probe contact area of 1.372×10−2 cm2 and capacitance was measured at a frequency of 1 MHz by the C-V map produced by the Four Dimension, Inc. The average dielectric constant is determined from 5 times measurements within 5% accuracy. A pressure sensing sheet named the I-Scan® produced by Nitta Harrs Co. LTD was placed between brush and wafer. The detailed experimental apparatus has been introduced in our previous report [3]. Brush was rotated at various rotation rates with and without ultra pure water flow on wafer. Dynamic pressure values at each measuring sensor cell were monitored and recorded during brush scrubbing.

3. Results and Discussion

Figure 1 shows shear force as a function of brush rotation rate in dry, which represents no ultra pure water (UPW) flows and in wet, which represents UPW flows, on the conditions of 5.5 kPa down pressure on the Cu wafer. Based upon shear force behavior in Fig. 1, brush scrubbing condition was separated below 200 rpm (call as Field I) and higher than 200 rpm (Field II). When the brush rotation rate is lower than 200 rpm (field I), shear force decreased in both dry and wet condition. On the other hand, when the brush rotation rate is higher than 200 rpm (field II), shear force increased significantly in wet, while shear force in dry remains the same value. The result that increase of shear force only in wet in field II suggests that increase of shear force may be contributed by hydrodynamic effect.

To clarify the brush contact kinematics on a wafer, dynamic contact of brush on wafer were inspected by a mean of a pressure sensing sheet. Figure 2 shows the maps of pressured area (a) 50 rpm in dry, (b) 50 rpm with UPW flow and (c) 500 rpm in UPW flow during brush rotation. Different colors of the pressurized sensor cells in the pressure sensing sheet express...
different down pressure. In Fig. 2 (a), each brush nodule was clearly identified. On the other hand, in Fig. 2 (b), pressurized area was generated between nodules and these areas are considered to contribute to increase total pressurized area during brush scrubbing. Moreover, this phenomenon becomes obvious at 500 rpm, as shown in Fig. 2 (c). Therefore, increase in pressurized area between nodules is believed to be explained by hydrodynamic model that higher velocity of fluid increase pressurization on non-contact area. Figure 3 shows average down pressure, pressurized area, and down force as a function of brush rotation rate in dry and wet measured by the pressure sensing sheet. The average down pressure was an average value of pressures at all pressurized sensor cells in measuring area. Down force is calculated by

\[ F_d = p_d A \]  \hspace{1cm} (1)

where, \( F_d \) represents down force of brush on the wafer, \( p_d \) represents the average down pressure and \( A \) represents pressurized area. While no significant difference of pressurized area was observed in both dry and wet in lower brush rotation rate. In higher brush rotation rate, pressurized area increased significantly in wet while a constant value was kept in dry. These results reveal that pressurized area by fluid increased with increasing in brush rotation rate, especially at high brush rotation rate. On the other hand, the average down pressure in wet decreased in low brush rotation rate, then they were leveled off in higher brush rotation rate. Since down force is a product of the down pressure and total area, decrease in down force is led by decrease in average down pressure in low brush rotation rate, while increase in it is led by increase pressurized area in high brush rotation rate.

Shear force is given in

\[ F_s = \mu F_d \]  \hspace{1cm} (2)

where, \( F_s \) represents shear force generated by friction between brush and wafer, and \( \mu \) represents coefficient of dynamic friction between brush and wafer. According to eq.2, increase in shear force in field II in Fig.1 is considered to be increased by increase in down force led by increase in pressurized area, while decrease in shear force in field I in Fig.1 is considered to be a result of decrease in down force led by decrease in average down pressure.

In Fig.1, when down pressure increased to 6.9 kPa at 200 rpm, the shear force value is found to be almost equal to one at 5.5 kPa down pressure at 500 rpm brush rotation rate and another at 5.5 kPa down pressure with 50 rpm brush rotation rate. Three equivalent conditions to obtain the same shear force value are consequently found: the condition 1 is low brush rotation rate with low down pressure in field I (such as brush rotation rate 50 rpm on 5.5 kPa down pressure), the condition 2 is high brush rotation rate with low down pressure in field II (such as brush rotation rate 200 rpm on 6.9 kPa down pressure), and the condition 3 is low brush rotation rate with high down pressure in field II (such as brush rotation rate 500 rpm on 5.5 kPa down pressure). The results of residue particle on the slurry contaminated Cu wafer after brush scrubbing in all conditions indicated to remove residue particles well. There results are considered to be attributed by the compatible shear force values.

The scratch formation on the fluorocarbon film was found at high down pressure (Condition 2). Apparently reduction of down pressure is a favorable direction to reduce damage generation on an ultra low-k dielectric.

4. Conclusions

Condition to reduce damage on brush scrubbing in post CMP cleaning was proposed by analyzing contact characteristic on the advanced non-porous ultra low-k dielectric, fluorocarbon film. Increasing down pressure helps particle removal efficiency, but scratch generation and degradation of chemical structure and electrical properties of the low-k fluorocarbon film also are occurred. Increasing brush rotation rate at lower down pressure results in satisfied electric properties, good particle removal efficiency and scratch reduction. These results reveal that increase contribution of fluid flow by increasing brush rotation rate with lowering down pressure can be direction for future low-k compatible devices.

References