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Prediction of polishing pressure distribution in CMP process with airbag type wafer carrier

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This paper presents a CMP process analysis considering an airbag type wafer carrier, which is used in semiconductor devices manufacturing. In the CMP process, a wafer is compressed against the polishing pad inside the wafer carrier, which consists of the retainer ring and the membrane film. Structural analysis model is developed to estimate contact pressure distribution over the wafer surface considering the airbag compression behavior. The polishing experiment without wafer rotation indicated a unique pressure variation around the trailing edge of the wafer. The developed analysis estimated the same phenomena accurately and clarified the mechanism deteriorating the polishing pressure uniformity.

Polishing; Finite element method (FEM); Modelling

1. Introduction

Preston's law dictates that the material removal rate (MRR) in polishing is typically proportional to the polishing pressure [1]. This fact demands that the polishing pressure, i.e., normal stress acting on the wafer surface by polishing pad contact, must be controlled accurately to achieve precision Chemical Mechanical Polishing (CMP) [2]. Thus, design of the wafer carrier mechanism becomes one of the most important elements to regulate the polishing pressure distribution. Particularly, polishing pressure variation around wafer edges is crucial. While a number of wafer carrier structures have been proposed so far [3], airbag type compression mechanism with a retainer ring is a de-facto standard for today's semiconductor manufacturing [4]. In this mechanism, back side of the wafer is compressed by the airbag consisting of a soft thin membrane film. As a result, compressive pressure distributes uniformly, and utilizing a multi-zone airbag pressure distribution can be regulated moderately. The retainer ring also plays a key role in the mechanism. Mechanically, it keeps the wafer inside the carrier but also calibrates the polishing pressure around the wafer edge area.

Although polishing pressure distribution can be adjusted up to a certain extent by airbag type wafer carriers, further improvement is demanded to increase the yield rate in semiconductor manufacturing. Computer simulation of polishing pressure distribution can assist optimization of the structural design of the CMP machines and help to determine optimal process parameters. Researchers have been focusing on the development of analytical simulation models [4,5] to predict pressure distribution. Accurate polishing pressure prediction requires an elasto-hydrodynamic lubrication (EHL) analysis model to tackle the tribological phenomena in CMP process [6]. Pad surface asperity contact against wafer has significant impact on the polishing performance [7]. The CMP analysis model considering nonlinear elasticity due to the pad surface asperity has been developed and the importance of consideration of its physical properties was indicated to predict polishing pressure distribution especially around wafer edge area [8,9]. Three-dimensional (3D) analysis models can incorporate influence of relative motion of the wafer, the polishing pad and the retainer ring and thereby enable accurate prediction of pressure distribution [10] over two-dimensional (2D) models [4]. Apart from modelling the material removal, experimental verification of developed models is another challenge. There is short of experimental data and critical knowledge of process parameters. Particularly, accurate modelling and experimental validation on CMP process with the airbag type wafer carrier structures have not been extensively reported in the literature.

In this paper, a novel computationally-efficient and accurate model for CMP process performed on airbag type wafer carrier machines is developed. A novel contribution is the detailed modelling of multi-zone airbag swelling inside wafer carrier, and relative motion kinematics between moving parts. The nonlinear elasticity of polishing pad due to surface asperity is identified through pad compression tests. Furthermore, an experimental investigation technique to validate the model accuracy is presented.

2. Development of CMP process model with an airbag type wafer carrier

Fig. 1 shows a schematic illustration of typical CMP process performed on an airbag type wafer carrier. Wafer surface is compressed against the polishing pad and relative motion is generated by rotating the wafer carrier and the platen simultaneously. Compressed air is supplied into the airbag and compression on the back of the wafer through a thin membrane film is applied. Today's CMP machines are equipped with advanced multi-zone airbags and thus this enables fine control on compression pressure distribution along a radial direction within a certain extent. On the other hand, geometry of the membrane film for multi-segmentation is complicated, and hence its modelling and simulation are challenging. As shown in Fig.1, wafer contacts the internal face of the retainer ring and thus it is retained inside the wafer carrier. The retainer ring compresses the polishing pad around periphery of the wafer independently. This function is a key to regulate the MRR around wafer edge.

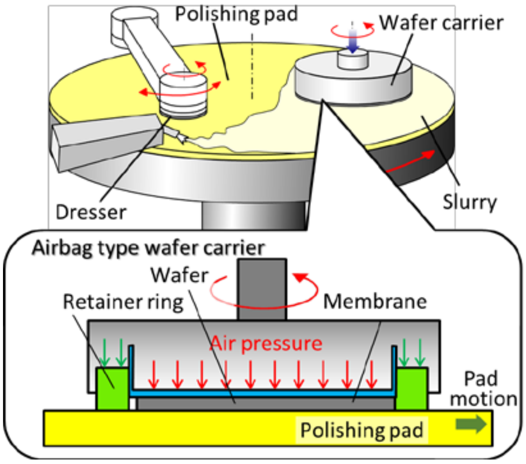


Fig. 1. Schematic illustration of general configuration of CMP process.

In this study, mechanics of a conventional CMP machine equipped with the airbag type wafer carrier is modelled. Proposed model considers rotational kinematics of the platen and polishing head during polishing process. Assuming that the process operates at a steady state, the dynamic motions and resultant friction due to the slippages between the wafer, the polishing pad, and the retainer ring are modelled. In order to attain highly-accurate analysis, influence of airbag compression pressure and nonlinear elasticity of the polishing pad are also taken into account. The procedure for calculation of the polishing pressure distribution is summarized in Fig. 2 and compared to conventional methods utilized in industry [4,5].

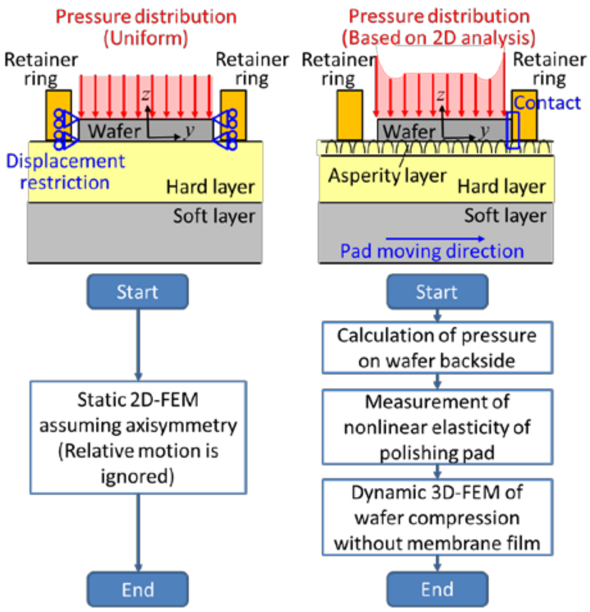


Fig. 2. Comparison of conventional (left) and proposed (right) analytical models.

Since the process model is extremely large-scale, analyses for the airbag swelling and the complex contact behaviour of the wafer-pad-retainer ring assembly are separately carried out. It should be noted that a simultaneous 3D analysis for all functionalities is unrealistic due to high computational cost. Firstly, a static structural analysis of the airbag is implemented by using finite element method (FEM) and only contact pressure distribution at the interface between the wafer and the membrane film is calculated in advance. As the membrane film is thin and its geometry is complicated as compared with other elements, 2D axisymmetric FEM is applied with a fine mesh. By interpolating the contact pressure distributions calculated in 2D FEM, compression pressure distribution acting on the back of the wafer is estimated. Secondly, nonlinear elasticity of the polishing pad is measured by utilizing the pad compression tester as shown in Fig. 3 [9]. Analysing stress-strain curves measured through the compression tests, mechanical properties of the polishing pad is identified. In the present study, a double-layered Polyurethane pad consisting of a hard upper layer and a soft cushion layer is utilized. The top surface of the hard layer is filled with asperities, creating nonlinear elasticity. Hence, the polishing pad is modelled as a structure stacked with three layers in series, i.e., asperity layer, rest of the hard layer (bulk hard layer), and the cushion layer [9]. For the asperity layer, Greenwood-Williamson model [11] is utilized to simulate nonlinear elasticity. Linear elasticities are assumed for the bulk hard layer and the cushion layer. Table 1 shows identified parameters through the compression tests.

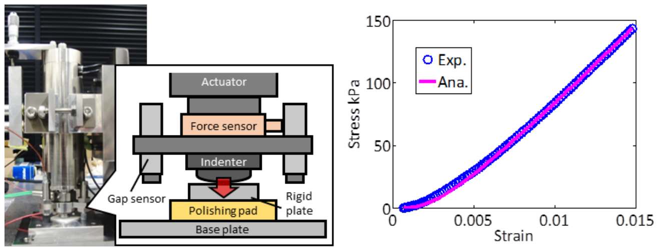


Fig. 3: Pad compression tester (left) and stress-strain curves (right).

Table 1 Material properties of polishing pad for simulations.

Upper hard pad	Asperity layer	Yung's modulus	MPa	132
		Poisson's ratio		0.3
		Standard deviation of asperity height	μm	5.24
		Radius of hemisphere	μm	50
		Asperity density	mm^{-2}	200
	Bulk hard layer	Yung's modulus	MPa	101
		Poisson's ratio		0.3
Lower soft pad	Cushion layer	Yung's modulus	MPa	7
		Poisson's ratio		0.3

Finally, 3D FEM considering the wafer, polishing pad, and retainer ring is performed. The wafer back side pressure calculated in the first step of airbag analysis is applied as a boundary condition. In order to take the influence of relative motion into account, nonlinear Arbitrary Lagrangian Eulerian (ALE) method [8,10] is applied, and so the influence of nonlinear elasticity and relative motions could be considered. Contacts between wafer-pad, wafer-retainer ring, and pad-retainer ring are considered in the structural analysis, respectively.

3. Evaluation of pressure distribution in stop polishing

This section validates the performance in pressure distribution estimation of the proposed model through "stop polishing" experiment. Schematic illustration of the CMP process analysed in the present study is illustrated in Fig. 4. A diameter and a thickness of the wafer are set to 300 mm and 0.75 mm, respectively. As the geometries of the wafer edge and retainer ring have significant influence on the polishing pressure prediction, their profiles are measured after the experiment and used in the FEM model. In order to calculate the pressure distribution at the back side of the wafer, actual membrane geometry is taken into account under practical air pressure conditions that are empirically optimized to achieve good MRR distribution. Friction coefficient between the wafer and polishing pad is experimentally identified to be 0.3. Rotation speed of the polishing pad is set to 85 min^{-1}, while wafer, membrane, and retainer ring are stationary, i.e., "stop polishing".

The "stop polishing experiment" is conducted on a commercial CMP machine with an airbag type wafer carrier. Tetraethyl orthosilicate (TEOS) blanket film wafers were polished by fumed silica based slurry. A double-layered polishing pad with concentric grooves on the top surface was used. When the pad groove has enough depth with even distribution, the influence of fluid pressure generation on the process is considered to be negligible. The fluid pressure distribution is, therefore, ignored and EHL analysis is not implemented in the present study. MRR distribution around wafer edge was measured to evaluate polishing pressure distribution. Preston's law dictates;

$$k_p p = \frac{MRR}{v} \quad (1)$$

where v is relative speed, p is polishing pressure, and k_p is Preston's coefficient, which also represents the polishing efficiency. As shown in Eq. (1), normalized MRR, i.e., the measured MRR divided by relative speed v, is a product of k_p and p. Since polishing pressure is proportional to the normalized MRR, actual polishing pressure distribution can be evaluated indirectly from measured MRR distribution. It is also noted that averaging of MRR at the same wafer radius does not occur in the stop polishing unlike in the general polishing with wafer rotation.

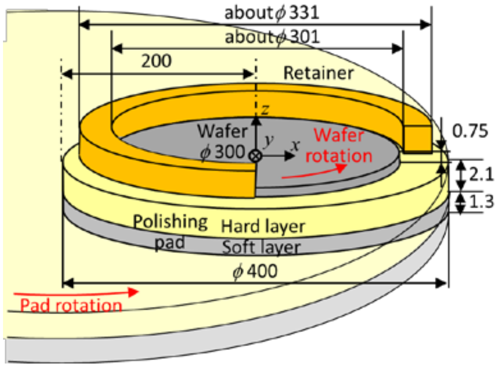


Fig. 4: Structural analysis model.

Fig. 5 shows distributions of predicted polishing pressure and calculated normalized MRR on the wafer. Each result is normalized by a mean value. Simulated polishing pressure distributes almost evenly. On the other hand, local pressure increase can be observed around the trailing edge of the wafer in the simulation. The normalized MRR distribution shows a good agreement in this variation around the trailing edge. The trailing edge contact of the wafer to the retainer ring is assumed to cause this uneven distribution. On the other hand, the normalized MRR has another peak around (x,y)=(-140,0). As the local polishing pressure increase cannot be estimated around the same area in the proposed simulation, it is thought that Preston's coefficient may have increased at this area in the real CMP process. The same phenomenon has been reported based on slurry flow simulation and experiments in several literatures [12]. In other words, polishing efficiency distributes in an uneven manner underneath the wafer. Therefore, accurate prediction of MRR requires estimation of the position varying Preston's coefficient.

Fig. 6 demonstrates surface deformation of the wafer, the retainer ring and the polishing pad in y-z plane. Calculated indentation depths of the wafer and the retainer ring are about 10 µm. As the polishing pad moves from left to right, friction force acts upon the wafer in the relative motion direction. The friction force is balanced by contact force of the wafer trailing edge against the retainer ring. Although the wafer location is retained inside the wafer carrier by this contact, the contact pressure between the wafer-retainer ring becomes significantly high due to large friction force acting on the wafer. This high contact stress causes micrometer-ordered deformation of the retainer ring in a direction perpendicular to the pad surface. As this deformation of the retainer ring contributes to further deformation of the polishing pad surface as shown in Fig. 6, contact stress of the wafer around the trailing edge is disturbed. Hence, influence of the trailing edge contact on the polishing pressure distribution is not negligible.

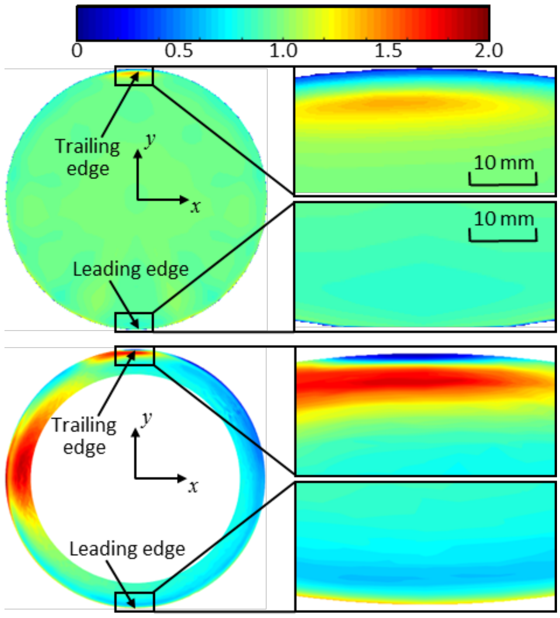


Fig. 5. Simulated contact pressure distributions (upper) and normalized MRR distribution (lower).

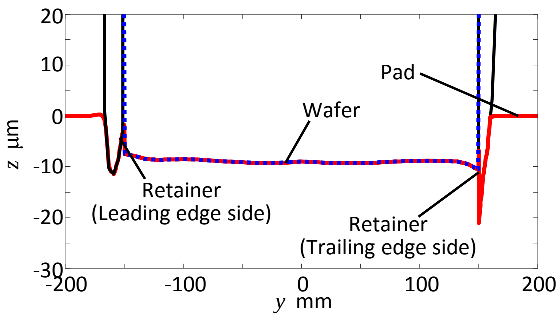


Fig. 6. Estimated contact surface deformations of polishing pad, wafer and retainer ring.

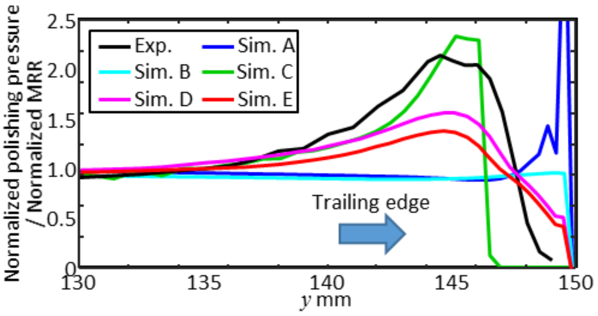
4. Investigations on the accuracy of modelling

Estimation accuracy significantly depends on the fidelity of the process model, imposed boundary conditions and process parameters. The trailing edge contact, nonlinearity of the pad surface asperity, and the wafer backside pressure distribution greatly affect accuracy of predictions. In this section, contact pressure profiles are estimated with or without each modelling element and compared against experimental results. Analytical conditions are listed in Table 2. In Sim-A and Sim-B, rotation centers of the wafer and the retainer ring are assumed to be identical eliminating any contact at the trailing edge. In Sim-A and Sim-C, pad surface asperity is ignored and only linear elastic properties are assumed. In Sim-A and Sim-D, uniform wafer back side pressure is assumed ignoring pressure distribution by means of multi-segmented membrane. Sim-E is the full-featured version of the proposed analysis.

Fig. 7 shows the normalized MRR profile "Exp" and the simulated polishing pressure profiles "Sim" around the trailing edge and the leading edge in stop polishing. Experimental result around the trailing edge indicates pressure increase at *y*=145. The variation at the trailing edge is significant as compared to the leading edge. Sim-D and Sim-E show a good agreement with the experimental results unlike Sim-A and Sim-B. Sim-C also captures similar variation partially regardless of pad asperity modelling. However, the polishing pressure suddenly drops to zero, which disagrees with the experimental result. Thus, it can be concluded that the accuracy in prediction significantly depends on the trailing edge contact modelling.

Table 2 Conditions for analytical investigations.

Simulation type	Trailing edge contact	Asperity layer on polishing pad	Wafer back-side pressure distribution
A (Conventional)	Not considered (concentric)	Not layered	Uniform distribution
B	Not considered (concentric)	nonlinear	Multi-segmented membrane
C	Considered	Not layered	Multi-segmented membrane
D	Considered	nonlinear	Uniform distribution
E (Proposed)	Considered	nonlinear	Multi-segmented membrane



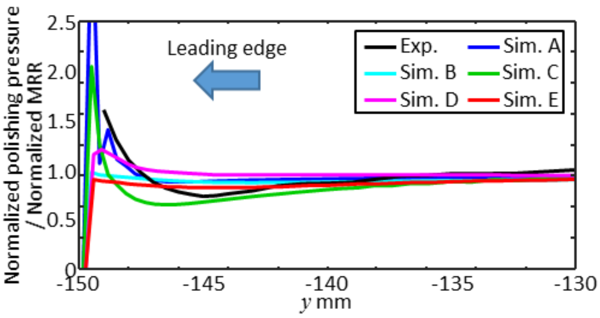


Fig. 7. Polishing pressure profiles around trailing edge (upper) and leading edge (lower) comparing with normalized MRR profile.

Proposed analyses are implemented considering the wafer rotation of 85 min^{-1}, which is identical to the platen rotation speed. In this case, material removal rate is averaged at the same radius due to wafer rotation. Fig. 8 demonstrates normalized MRR profile and radially-averaged polishing pressure profiles, where the calculated polishing pressure is averaged at the same radius. MRR profile fluctuates around the wafer edge. The rise in MRR around *y*=145 is considered to be caused by the polishing pressure increase around the trailing edge. On the other hand, MRR increase at *y*>148 is due to the polishing pressure increase around other edge region as shown in the leading edge. Hence, polishing pressure prediction not only around the leading edge but also around the trailing edge is important to predict resultant MRR profile. Sim-E shows better fit to MRR as compared with Sim-D. Hence, consideration of the airbag compression is important to predict MRR. Exp seems to exist in between Sim-C and Sim-E. This fact indicates that consideration of asperity layer is important but the parameters identified in the present study might be not appropriate. In addition, Preston's coefficient may distribute unevenly. As shown in Fig. 5, active abrasives in the slurry may be concentrated around (*x*,*y*)=(-140,0). Hence, predictions of not only polishing pressure distribution but also Preston's coefficient are important to predict MRR profile accurately.

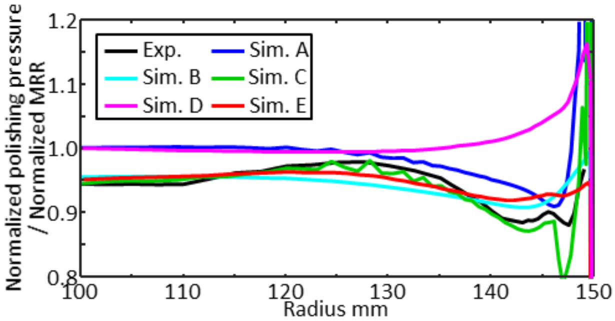


Fig. 8. Radially-averaged polishing pressure profiles compared with MRR.

5. Conclusion

This study presented an analytical model of CMP process performed with airbag type wafer carriers. Accuracy of polishing pressure predictions is analysed through a series of CMP experiments. Stop polishing experiment revealed significant MRR variation that occurs around the wafer trailing edge. Analytical investigation clarified that the MRR variation around the wafer trailing edge is caused by the uneven polishing pressure distribution due to the wafer-retainer ring and retainer ring-pad contacts. The polishing pressure variation directly affects resultant MRR profile in practice. Hence, the importance of accurate contact pressure prediction not only around the leading edge but also around the trailing edge is shown. Experimental results also clarified that consideration of uneven Preston's coefficient distribution is necessary to attain a more precise prediction of the MRR profile.

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