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

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ABSTRACT

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 behaviour. 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.

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

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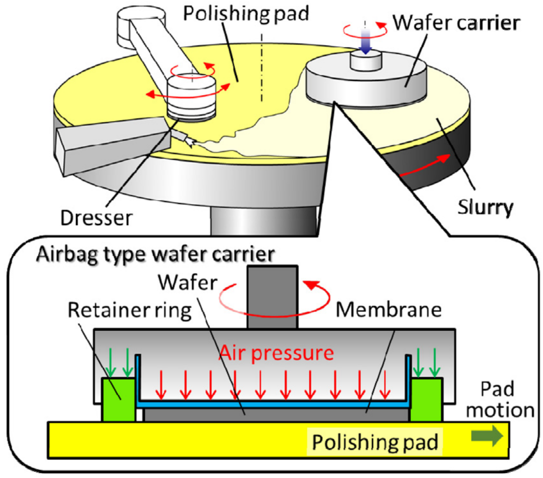

Fig. 1. Schematic illustration of general configuration of CMP process.

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.

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].

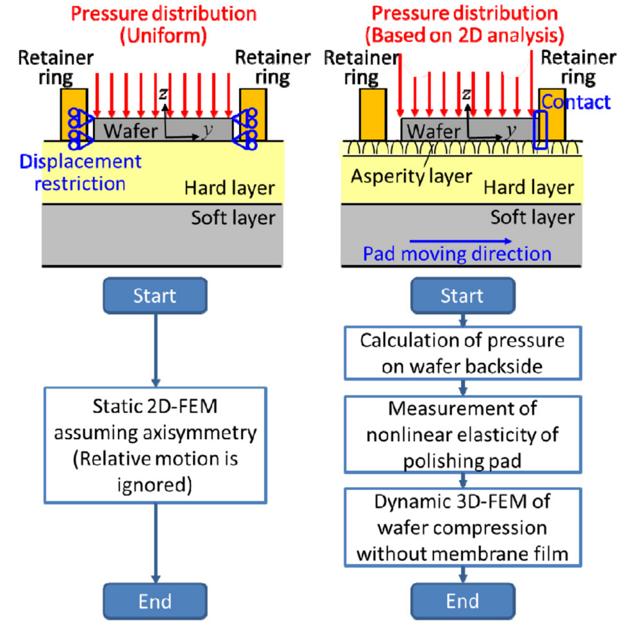

Fig. 2. Comparison of conventional (left) and proposed (right) analytical models.

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.

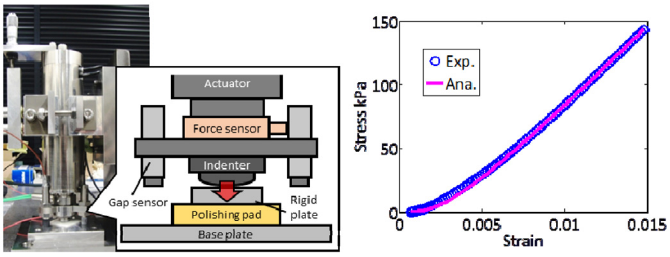

Fig. 3. Pad compression tester (left) and stress–strain curves (right).

Table 1
Material properties of polishing pad for simulations.

Upper hard pad	Asperity layer	Young'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	Young's modulus	MPa	101
		Poisson's ratio		0.3
Lower soft pad	Cushion layer	Young'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

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