Evaluation of Non-local effects in Chemical Mechanical Planarization

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Abstract

In Chemical Mechanical Planarization (CMP), within wafer non-uniformity (WIWNU) and within die non-uniformity (WIDNU) are particularly important. While the wafer pattern geometry sizes continuing reducing and varying within a die, CMP performance has been challenged on controlling step high, dishing and erosion uniformly within a die and from die to die across the wafer especially on the critical local structure during CMP process.

The objective of this work is to evaluate non-local effects of locally applied pressure. A locally applied pressure on the wafer translates to wafer-pad contact pressure that spreads beyond the area of load application. The spread has to be quantified to design an accurate pressure control strategy. Theoretical global contact pressure is added to local contact pressure generated through FEM simulation and is used to evolve wafer surface. The evolved wafer surface is then compared with experimental profile. Preston constant is fitted to a single experimental data point, and is then used to match the wafer profile. The model estimation error for non-local effects reduces as wafer modulus is decreased and pad modulus is increased.

Introduction

Chemical Mechanical Planarization (CMP) has emerged as a leading method for semiconductor surface planarization. Even though the physics of the process is still not completely understood at particle scale, the ability of the process to achieve global planarization has been beneficial for CMP over other planarization techniques.

Controlling WIWNU and WIDNU during CMP process has always been one of the most difficulties since CMP became an industry dominant planarization process. As we know that the local material removal rate depends on the local polishing conditions, such as localized polishing pressure, velocity, mechanical stress, slurry distribution, chemical reaction, polishing pad wear, pad compressibility, pad temperature, wafer structure and pattern density. As microelectronic feature sizes continue to shrink, the ability to planarize various substrates over wide ranging length scales has become an essential element of the process.

In order to improve global uniformity, one of the approaches is to adjust the local polishing pressure which is one of the key elements to control removal rate. The main impediment for this is the non-locality of the contact pressure when the load is applied. Hence the spill over of contact pressure into neighboring zones has to be studied to make any control strategy based on varying local pressure successful. The non-locality of contact pressure has been studied back in 1970s by Erdogan (Erdogan, 1974).

In the current paper, modeling of contact pressure at global scale is carried out using Fu and Chandra's model (Fu et al, 2003) and 2-D simulations are carried out at local scale to abet the notions of earlier theoretical understanding. Experiments are carried out and they agreed with predictions that have roots in both theoretical and numerical methods.

Experiment

The experiment is performed on a Strasbaugh nSpire (6EC) Polisher using 3 inch wafer size and IC 1000 polishing pad. An experimental pixel with 3x5mm size is placed on carrier at 15mm radius from the wafer center location as shown in Figure 1. The 5 psi (0.0344 MPa) polishing pressure is applied on the entire wafer area and the 20 psi (0.138MPa) polishing pressure was applied on the pixel only.

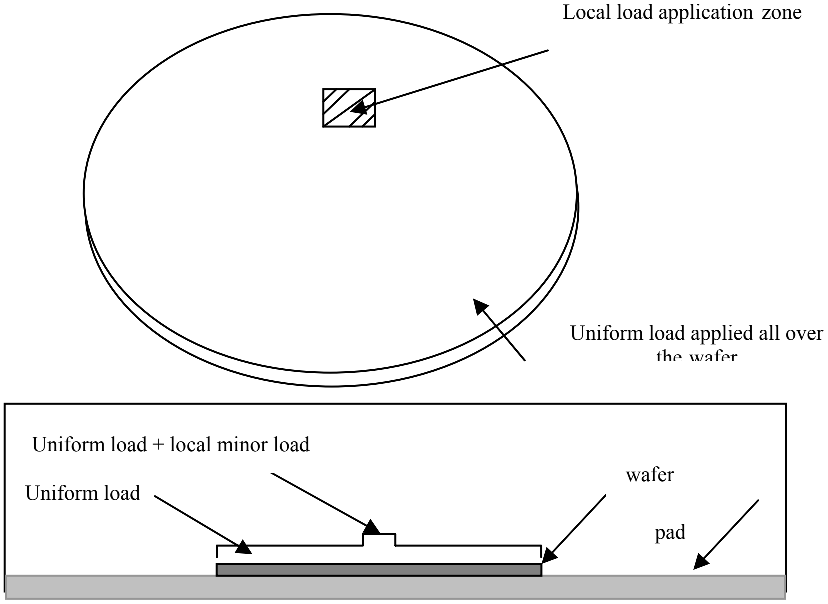


Figure 1: One Pixel location and local load configuration.

The interface between wafer and pad are modeled as Elastic Contact. The pad elastic modulus changes from 30 MPa to 190 MPa depending on the pad wetness degree. The wafer elastic modulus was around 70 GPa and adjustable due to the soft backing film.

With the set of up polishing parameter and conditions, the final surface profile is measured along the 3mm direction, which matches with the model prediction by adjusting various parameters.

Modeling and Discussion

FEM (ABAQUS) Solution

The aim is to get a solution of a wafer-pad contact pressure while a unit pressure is applied on the wafer "pixel". The wafer-pad is modeled as plate on half-space. The parameters used in the FEM (ABAQUS) [1] are showing in Table 1. The boundary conditions are listed in Table 2. Plane stress formulation is used. Global contact pressure is subtracted from resulting contact pressure to get contact pressure due to local pressure alone (Figure 2).

Part/*Property/Dimension*	**Wafer**	**Pad**	**Film**
Length(mm)	76	600	76
Thickness (mm)	1	2	1
Young's Modulus(MPa)	30000 - 70000 [2]	30-100 [2]	100
Poisson's Ratio	0.2 [2]	0.4 [3]	0.4

Table 1. Parts and their properties.

Part/*Boundary condition*	**Wafer**	**Pad**	**Film**
Side(DOF allowed)	Vertical Displacement	ALL	ALL
Top(DOF allowed)	ALL	ALL	Vertical displacement

Bottom(DOF allowed)	ALL	NONE	ALL

Table 2: Boundary conditions

For force equilibrium the area under the curve should be equal to the product of the loading zone length and the pressure applied. It is verified that the force equilibrium is satisfied and the analysis is excluded here for brevity.

It is also observed that the local polishing did not start below a particular local pressure. Hence the local pressure is adjusted to fit the final surface profile. Since the Preston constant changed with the pad and wafer properties, it is adjusted to fit the experimental data.

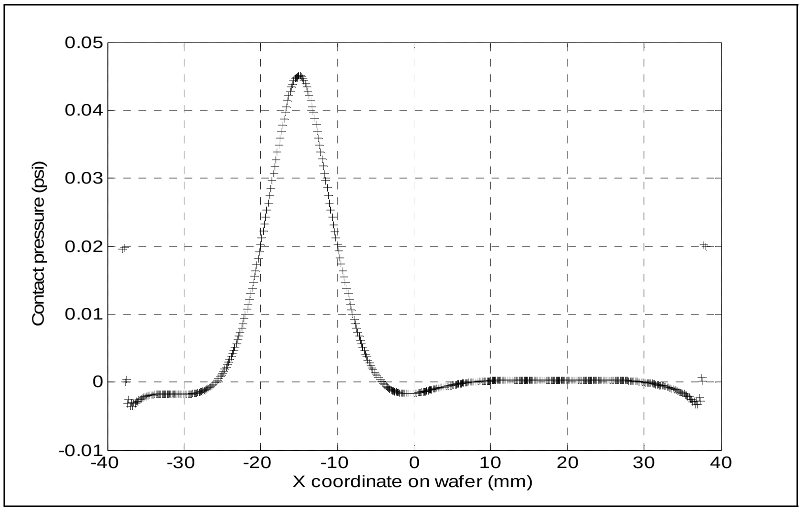


Figure 2: Response due to local 20 psi load (response due to both loads - global contact pressure)

The model of the material removal

The model of the material removal is assumed to follow Preston's linear equation in pressure and velocity and at local level MRR at any location *r*, *MRR(r)* is given by the following equation in terms of *P(r)* is pressure at location *r* and *V* is relatic velocity between wafer and pad.

$$MRR(r) = KP(r)V \qquad (1)$$

Equation (1) is applied to obtain the final surface profile from the initial one. It is assumed that the local pressure does not result in the change of global curvature.

There are two pressures applied on the wafer, a global uniform pressure and a local contact pressure. The global contact pressure sets of the curvature that is defined by variables a_0 and a_2. The contact pressure due to this curvature is given by Fu and Chandra [4,5,6].

$$\sigma_{zz}(r) = \frac{E}{\pi(1-\upsilon^2)} \frac{4a_2r^2 + a_0 - 2a_2a^2}{\sqrt{a^2 - r^2}} \qquad a = \text{radius of wafer} \qquad (2)$$

The local contact pressure is obtained from ABAQUS, and FEM software. The two contact pressures obtained are added to get the resultant contact pressure which determines the polishing rate at any location.

Preston constant change

The closer the pad and wafer moduli (Pad 190 MPa and Wafer 30 GPa against Pad 30 MPa and wafer 70 GPa), the lesser the spread of the contact pressure outside the region of pressure application. As the load is constant, the area under curve remains the same. In this case, when the spread increases, the peak contact pressure decreases, hence the Preston constant needs to be changed whenever the pad and wafer properties change.

The pad and wafer properties determine the spread of the contact pressure. The depth of the contact pressure profile determines the depth of polishing. The Preston contact is calculated based on the deepest point on the wafer surface as shown in Table 3.

Pad Modulus ▼ / Wafer Modulus ►	30 GPa	50 GPa	70 GPa
30 MPa	6.10E-08	7.10E-08	7.50E-08
60 MPa	5.65E-08	6.65E-08	7.35E-08
100 MPa	5.10E-08	5.70E-08	6.10E-08
140 MPa	4.55E-08	5.25E-08	5.70E-08
190 MPa	4.50E-08	4.80E-08	5.30E-08

Table 3: Variation of Preston constant with Pad and Wafer properties

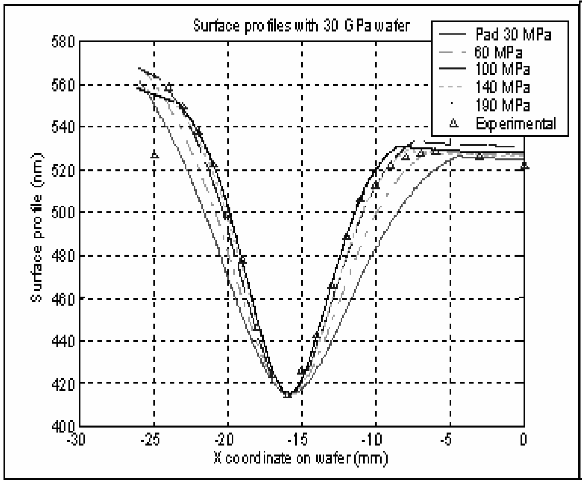
It is noticed that the global force equilibrium requires the wafer-pad contact pressure to remain constant. Since contact pressure is a function of the pad property and the contact pressure is set by the curvature, the pad property changes the curvature also changes accordingly to attain global force equilibrium.

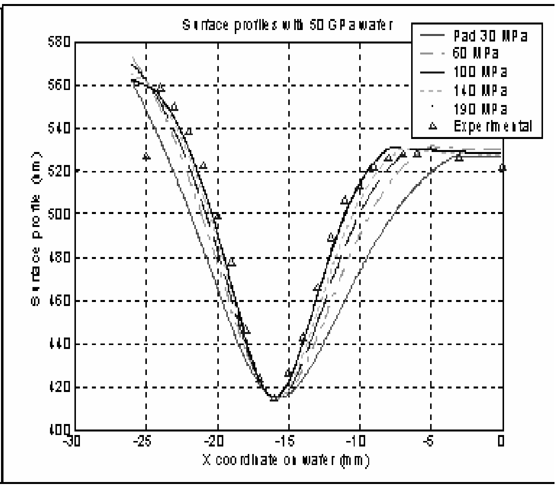
Variation of final surface profiles with Pad-Wafer properties

The predicted final surface profile for each pad and wafer property is compared with the experimental profiles and the corresponding RMS errors plotted in Table 4. The error is maximum for 30 MPa pad and 70 GPa for wafer and it is minimum for 190 MPa pad and 30 GPa wafer.

Pad modulus ▼/ Wafer Modulus ►	30 GPa	50 GPa	70 GPa
30 MPa	22.567	27.622	33.0269
60 MPa	14.2291	18.3531	21.5523
100 MPa	9.88035	13.9261	17.8978
140 MPa	7.59707	11.1147	13.8854
190 MPa	6.93772	8.67754	11.2984

Table 4: Comparison of RMS error (nm)





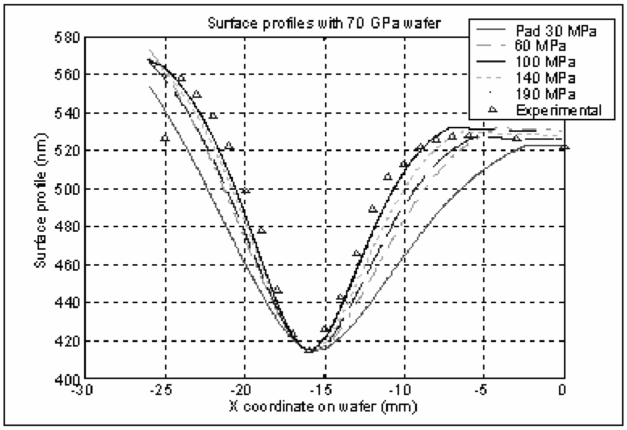


Figure 4: Final surface profiles with various wafer moduli (Clock wise from Top left)
(a) 30 GPa (b) 50 GPa (c) 70 GPa
(b)

For lower pad modulus and higher wafer modulus, the spread of the contact pressure increases and the Preston constant increases. The increase in spread of the contact pressure increases the RMS error. This is evident from the experimental data as it fits well with high pad modulus and low wafer modulus as shown in Figure 4 (a), (b) and (c).

It is evident from the Figure 4 that the pad and wafer properties actually influence the shape of the final surface profiles. The ratio of the wafer modulus and the pad modulus determines the spread of the contact pressure. The wafer modulus increases the ratio and the spread of polishing increases. As the pad modulus increases the ratio decreases and the spread reduces. This can also be inferred from the RMS error Table 4.

Conclusion

The objective of this work is to evaluate non-local effects in CMP for modulating local pressure. The initial experiment work has showed that using finite element method the contact pressure profile can predict evolution of the wafer surface progressively with time. The obtained wafer surface profile after certain time is compared with the experimental wafer profile after the same time of polishing. A representative value for elastic modulus is used to fit the experiment to the model. The model predictions of the model correlate well with experimental results for relatively higher pad modulus and low wafer modulus. The result can be used to polish the wafer with the numerical contact pressure profile obtained from ABAQUS (FEM). Various strategies to load the wafer locally are to be developed to improve the planarization.

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