RE-EXAMINING THE PHYSICAL BASIS OF PATTERN DENSITY AND STEP HEIGHT CMP MODELS

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ABSTRACT

Our group has proposed several chip-scale CMP models, with key assumptions including the notion of planarization length in the pattern density model [1], and step height dependent polishing rate in the density step height model [2]. In the effective density model, planarization length is the characteristic length of an elliptic weighting function based on the long-range pad deformation and pressure distribution during CMP. This semi-physical model is often adequate and usually gives a fitting error of a few hundred angstroms. As ever-shrinking device size pushes for tighter control of post CMP uniformity, however, we need a chip-scale CMP model with better accuracy.

In this work, we re-examine the physical basis for averaging weighting functions and step height dependence, particularly in the context of contact mechanics based model formulations. The comparison of the two models confirms that the analytical density and step height models can be viewed as approximations to the contact wear model. The study also suggests a new dependence of contact height on line space and pattern density.

INTRODUCTION

In chemical–mechanical polishing (CMP), excellent planarization (i.e., reduction in step height) of individual patterned features is achieved; however, global nonplanarity is unfortunately created due to differences in the underlying pattern, resulting in nonuniform oxide thickness across the die. The ability to predict the post-CMP oxide thickness for arbitrary chip layouts is critical for CMP and deposition process optimization, layout screening or density design rule checking, pattern density equalization (e.g., dummy fill), process control, and circuit impact analysis.

CMP models have usually focused either on wafer scale considerations (e.g., kinematic models of relative velocity, fluid flow models, pressure models), feature scale effects [3] or on layout pattern effects. Among the more promising approaches are contact wear or pad pressure based models by Chekina *et al.* [4], and Yoshida [5], which seek to solve for the local displacements and pressures of an elastic polishing pad in contact with the patterned wafer surface. Such models require time-stepped evolution of the surface, as well as discretization down to the size of the features of interest, and are computationally intensive if applied across an entire product chip.

An alternative approach has been proposed by Stine *et al.* in which analytic solutions are possible, based on calculation of the effective pattern density across the chip [6]. This approach is coupled to a rapid characterization methodology using test patterns and test masks, so that the essential model parameters can be estimated for a given CMP process [7]. The effective pattern density model builds on a key concept of planarization length, which describes the averaging range of a pad and process over pattern densities. The step height density model [2] extends the effective density model and adds to this a removal dependence on local step heights. The models have been demonstrated for production CMP process with a root-mean-square error of a few hundred angstroms. To further understand the basis for, and seek improvement to, these semi-empirical models, we revisit some key assumptions, such as the planarization length and step height dependence. In particular, we study how the pattern density and step height dependent models serve as approximations to the physically based contact wear model.

In this paper, we will briefly review the effective density model and the step height model, with an emphasis on the key assumptions, as well as the contact wear model. Then, we present a series of simulations using the contact wear model to study the planarization length and step height ideas. By analyzing the simulation results, we show that the step-height density assumptions and approximations are appropriate. We also gain some insights into directions for improvement of these models.

REVIEW OF MODELS

The pattern-density-based CMP model, proposed by Stine *et al.* [6], reformulates Preston's equation (1) which has a dependency on pressure P, relative velocity v, and empirical Preston coefficient k_p into a function of blanket wafer polish rate K and effective pattern density $\rho(x,y)$

$$\frac{dz}{dt} = -k_p P v = \frac{K}{\rho(x,y)} \tag{1}$$

The equation gives "up area" polishing rate, and assumes that no "down" area polishing occurs until the local step height has been removed, after which the wafer is polished at the blanket removal rate. Here ρ is the effective density dependent on lateral location *(x,y)* on the layout, and it is assumed to be independent of time evolution. The effective density is calculated from the local density distribution by averaging over a square area around the local *(x,y)* position, as illustrated in Figure 1. The range of the area is usually referred to as *planarization length*. In calculation of effective density, a square shape is not the only possible choice of weighting function; Ouma suggests that an elliptic weighting function is more physically close to the bending of the polishing pad [1]. He compares the performance of the elliptic weighting function with other functions, such as square, cylinder and Gaussian shapes, and finds the elliptic and Gaussian weighting functions to have the best performance. Another popular weighting function has the form $1/(r+a)^b$. Figure 2 shows 3D plots of all five weighting functions. After picking

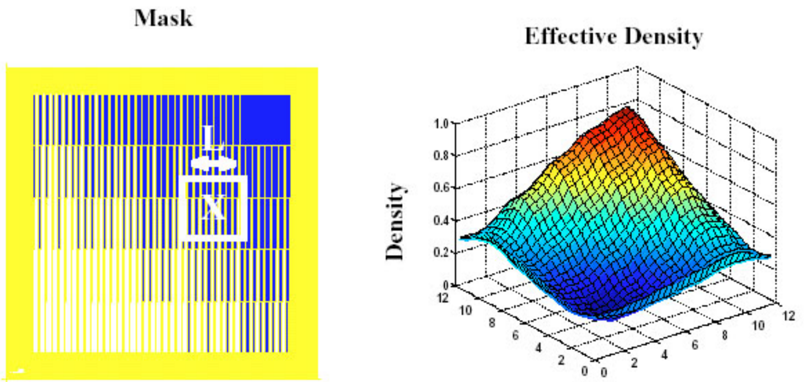

Figure 1. Illustration of calculation of effective density from mask layout using a square shape weighting function. *L*, denoted in the left picture, is the planarization length.

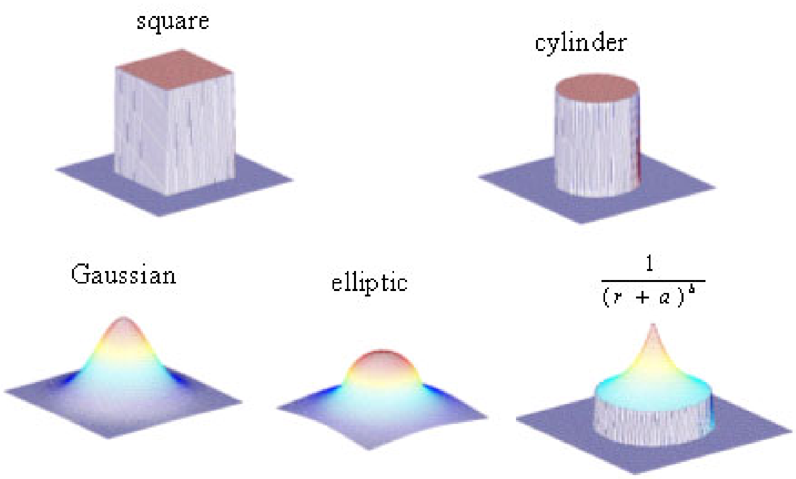

Figure 2. Different weighting functions in calculation of effective density.

the weighting function and planarization length, the effective density can be calculated efficiently from the local density using the FFT.

The effective density model describes the long range bending of the pad over the wafer, and assumes no “down area” polish until the local step height is removed, i.e. treats the pad as incompressible over the feature scale. The step height density model builds on the effective density model and takes the local bending of the pad into account. If the step height is large, the pad does not touch the down area and the effective density model is applied in this regime. If the step height falls below a certain height, defined as the contact height h_c, the pad starts to contact the down area and polishing occurs at both up and down areas. The assumed removal rate dependency on step height is illustrated in Figure 3.

Step height and effective density models make key assumptions related to the use of a weighting function and dependence of removal rate on step height. These assumptions greatly simplify the problem, and enable closed-form prediction of final film thickness. However, the accuracy of the model depends on these assumptions, and we would like to verify them.

In this paper, we will use the contact wear model, as described by Chekina [4] and Yoshida [5], as a probing tool. Its concept is to relate local pressures on the wafer surface to the polishing pad displacement, and use the local pressures to derive local removal rates assuming the polish rate is linearly proportional to the pressure. As the film surface evolves through time, the pad

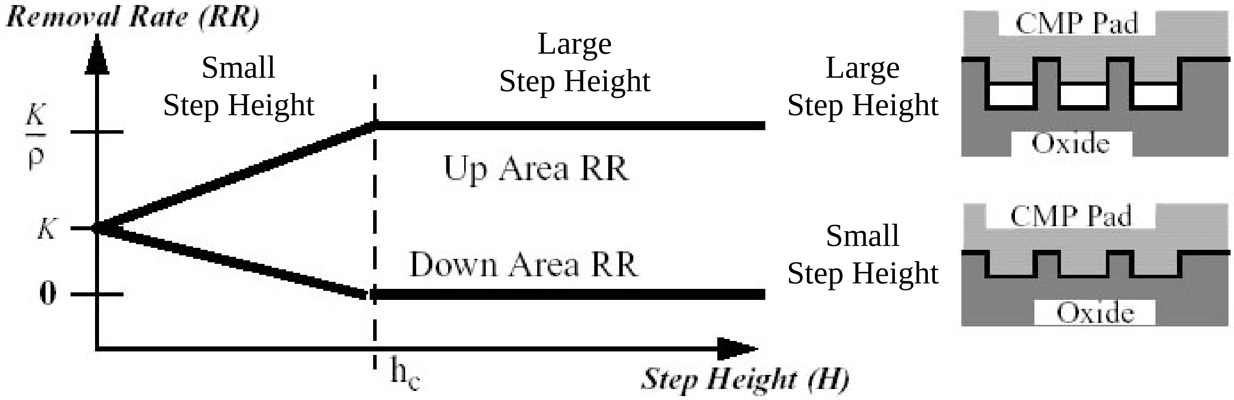

Figure 3. Removal rate dependence on step height.

displacement is changed, and thus local pressures and removal rates are modified. The simulation surface is discretized into elements, and a time-stepped algorithm is used to determine the final post-CMP film surface. Yoshida [5] describes a boundary element method to solve the matrix form of this equation.

Because 2D contact wear simulation is computationally expensive for feature-scale calculation over die-size structures, we will apply only 1D simulation in this paper. For 1D structures with periodic boundary condition, the pressure distribution is related to the pad displacement as [8]

$$w(x) = \frac{1-\nu^2}{\pi E}\int_{-\frac{L}{2}}^{\frac{L}{2}} \ln\left|\sin\frac{\pi(x-s)}{L}\right| p(s)ds \qquad (2)$$

where *w(x)* is the displacement of the pad at point *x* on the wafer surface, *p(x)* is the local pressure of the pad, *v* is Poisson's ratio of the pad, and *E* is the Young's modulus of the pad.

SIMULATION AND RESULTS

The contact wear model can be used to predict the film profile as a function of time. We choose the Young's modulus as 100MPa, wafer pressure as 5MPa and blanket removal rate as 275nm per min. We run the contact wear for a 60 second polish gathering data on the surface profile at 5 second intervals. The profile evolution is shown in Figure 4.

Step height model

We first consider the assumption in the step height model that when the step height is larger than the contact height, there is no polish in the down area, and that when the step height falls below the contact height, the removal rates of both areas converge linearly to the blanket removal rate. We run the contact wear calculation on periodic structures with 50% pattern density with various step heights, and plot the pressure and step height relationship in Figure 5. It is not identically the linear relationship as assumed, but the linear assumption captures the relationship quite well.

We next consider how to determine the contact height, which is a critical parameter in the step height model. In applying the semi-empirical density step height model, the contact height is usually determined based on experimental data gathered from test wafers. Our goal here is to

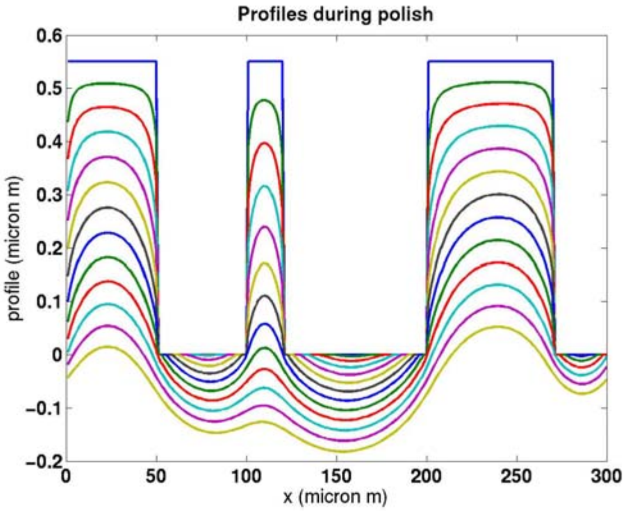

Figure 4. Profile evolution over a 60 second polish at 5 second intervals.

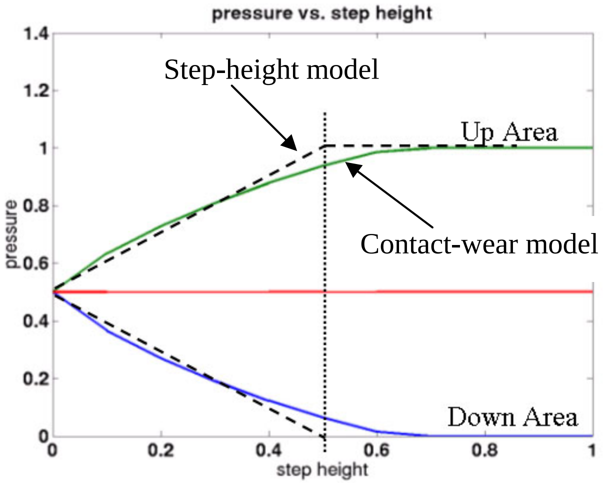

Figure 5. Simulated pressure dependence on step height.

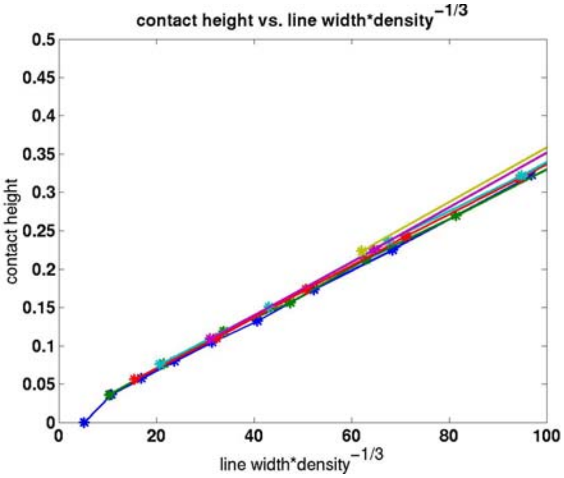

Figure 6. Contact height is fitted approximately linearly with (line space)/(density)$^{1/3}$.

explore a contact-wear basis for determination of contact heights. We choose seven sets of structures with pitches 20, 30, 40, 60, 80, 120 and 240 microns, and each set contains nine structures with densities from 10% to 90%. We can generate a pressure dependence on step height for each structure using the contact wear model, and we can fit the contact height to this data. By fitting the contact heights to line width, line space, and density, we find the best fit is *(line space)/(* $\rho^{1/3}$ *)* as shown in Figure 6.

Pattern density model

To study the long range pattern density effect, we choose one row of the MIT STI mask as the 1D structures. We apply contact wear polish simulations with various Young's modulus and blanket removal rates. By fitting to the pattern density model with a Gaussian weighting function, we extract planarization length for each configuration of modulus and blanket removal rate. The two models agree with each other with root mean square error of 200-300 angstroms. The planarization length remains nearly constant as the blanket removal rate varies, and the planarization length increases linearly with the Young's modulus as expected, as illustrated in Figure 8.

CONCLUSIONS AND FUTURE WORK

We have re-examined key concepts and approximations in the pattern density step-height models using contact wear simulations. By comparison of the two models, we confirm that effective density and step height removal rate dependence are appropriate to the contact wear model approximations. The study also suggests directions for improvement of the current model; specifically, an empirical dependence of contact height on line space and pattern density has been proposed which merits further investigation. Contact wear model comparison may also provide insight into possible time or height dependencies of the planarization length. It is worth notice that although long-range and feature scale behaviors observed in experimental data can be generated by the contact wear model, realistic processes may require different contact wear

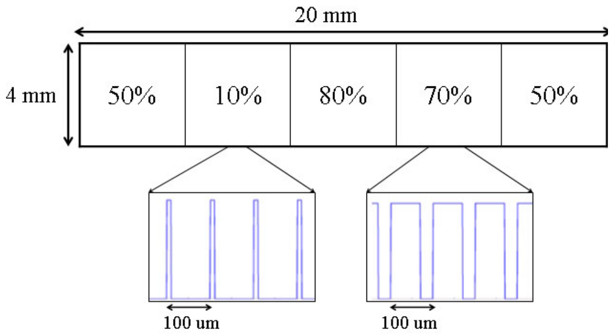

Figure 7. Structures of one row from MIT STI mask.

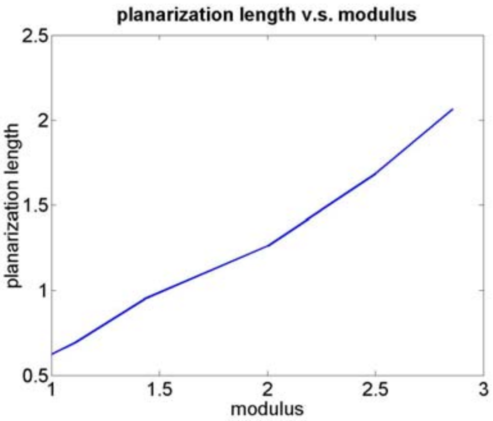

Figure 8. Planarization length response is approximately linear with respect to pad Young's modulus.

parameters at the two length scales. More work is needed to understand how the density step-height model can simultaneously approximate the contact wear model at both scales.

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