CMP Modeling and Characterization for Polysilicon MEMS Structures

Brian Tang and Duane Boning
Microsystems Technology Laboratories, MIT
60 Vassar St., Bldg. 39-328, Cambridge, MA 02139

ABSTRACT

The current bedrock technology for integrated circuit (IC) planarization, chemical-mechanical polishing is beginning to play an important role in microelectromechanical systems (MEMS). However, MEMS devices operate with bigger feature sizes in comparison to ICs, in order to fulfill mechanical functions. We present an experiment to characterize and model a polysilicon CMP process with the specific goal of examining MEMS-sized test structures. We utilize previously discussed CMP models and examine whether assumptions from IC CMP can be applied to MEMS CMP. An analysis of the data collected points to a polishing dependence on not only pattern density, but also partly on feature size or feature configuration. The existing pattern density and step height CMP models are able to capture the major trends in up and down area polishing. However, certain layout features relevant to MEMS are difficult to predict, motivating the need for further model development and application.

INTRODUCTION

Chemical-Mechanical Polishing (CMP) serves as the dominant method for wafer planarization in the integrated circuit industry. However, most past work examining CMP has focused on the ever-shrinking feature sizes in integrated circuits. The microelectromechanical systems (MEMS) industry, on the other hand, does not necessarily gain the same benefits from miniaturization. Mechanical structures might require features orders of magnitude larger than transistor gates. Integrated circuit CMP models focus on oxide and other dielectrics, as well as on the polishing of copper interconnects. MEMS CMP must cover a broader set of standard and non-standard materials, such as silicon carbide [1]. Our study examines the polishing of polysilicon, a structural material used widely in MEMS devices [2].

Another important difference between IC and MEMS CMP relates to wafer bonding, an enabling technology for many types of MEMS devices. Fabrication creates die and wafer level features, but also increases surface roughness that can impede bonding; CMP can be used for surface preparation to decrease the surface topography and roughness, and can enable previously non-bonding wafer pairs to bond [3]. At the same time, the polishing process will also affect the wafer’s structural patterns. CMP may result in global nonplanarity caused by differences in pattern size or density across the die or wafer.

We model the CMP process using an analytical model originally proposed by Stine et al. [4]. This model produces analytical solutions for polishing based on effective pattern density across the target die [5]. Central to this model is the idea of planarization length, the distance over which the CMP process creates local planarization, but fails to remove global nonplanarity. The step height density model [6, 7] extends the effective density model by incorporating material removal dependence on local differences in height between up and down areas.

In this paper, we will review both the pattern density and step height density models. We will then apply these models to sets of experimental data to characterize our MEMS CMP process, as well as examine some unique issues related to CMP for MEMS structures.
REVIEW OF MODELS

Pattern density model

Proposed by Stine et al. [4], the pattern-density CMP model utilizes the wafer blanket removal rate $K$ and effective pattern density $\rho(x, y)$ to analytically determine how features are polished. This formula comes from Preston’s equation (1), and relates the polishing of features to pressure $P$, relative velocity $v$, and the empirical Preston coefficient $k_p$. 

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

The polishing rate applies to areas of raised features, or “up” areas. We assume that the “down” areas are not polished until all up areas are cleared away and the step height between “up” and “down” areas is reduced to zero. After this reduction, the model assumes that the wafer is polished at the blanket removal rate. Up area polishing depends on $\rho$, the effective density at location $(x, y)$ on the die, and remains independent of time. The effective density of position $(x, y)$ is calculated by convolving a filter function around each position, averaging the local density around the point $(x, y)$, as shown in Figure 1. The size of the filter function is called the planarization length. The planarization length incorporates assumptions about the behavior of the pad and process at a certain point $(x, y)$ and explains how close features in the surrounding environment must be in order to affect the polishing at point $(x,y)$.

![Planarization length](image)

**Figure 1.** The local density is convolved with the Gaussian filter to get the effective density.

The different density filters can take different shapes, such as squares, cylinders, Gaussian shapes, elliptical shapes, or cone shapes with the form of $1/(r+a)^b$. Ouma compared the effectiveness of several filter weighting functions, and found the elliptical shape to have the best performance [5]. The elliptical shape is thought to give the best performance because it is conceptually close to the physical bending of the CMP pad. Because the Gaussian also does an excellent job of approximating the model response and is computationally simple to use, the Gaussian is adopted in the work reported here. Once the filter function shape and planarization length have been selected, the effective density can be efficiently calculated by multiplying the fast Fourier transforms (FFTs) of the filter function and local density of the wafer.
**Step height density model**

Although the pattern density model encompasses long range bending of the polishing pad over the planarization length, it assumes that the “down areas” are not polished until the local step height is reduced to zero. The step height density model incorporates the idea of local pad bending, where the pad can compress and bend around local features [6], as originally described by Grillaert et al. [8]. Large step heights hold the pad up, resulting in no down area polishing. However, when the step height reaches or falls below the contact height $h_c$, both the up and down areas will be simultaneously polished. The removal rate depends directly on the step height and contact height, as seen in Figure 2. When above the contact height, the die polishes as in the pattern density model, where only raised features polish. At or below the contact height, both up and down areas polish. Because more material contacts the pad, the removal rate changes as the pad pressure is apportioned between up and down areas. When the step height dependence is finally removed by polishing, the whole die (both up and down areas) are polished at the blanket wafer removal rate.

![Figure 2. Removal rate dependence on step height.](image)

**Updated step height density model**

While the reviewed CMP models rely on pattern density to explain polishing non-uniformities, a different class of CMP models relies on contact wear due to localized pad pressure to explain polishing. These models, proposed by Chekina [9] and Yoshida [10], use the polishing pad displacement to map out local pressures on the wafer surface. By assuming a polishing rate linearly proportional to pressure, the local pressure map defines local removal rates. As the film surface evolves through time, the pad displacement is changed, and thus local pressures and removal rates are modified. When comparing the contact wear and step height density models, Xie et al. [7] contrasted the pressure and step height relationship for each model. While the two models followed the same trend, the contact wear model suggests a removal rate curve like that shown in Figure 3. Rather than having a distinct contact height, an updated step height density model proposed in [7] utilizes a continuous function to explain the dependence of removal rate upon step height. This model improvement also simplifies the calculation of material removed because the removal rate function is no longer discontinuous.
MEMS CMP CHARACTERIZATION EXPERIMENT

Characterization test mask

The test mask, shown in Figure 4, is designed with MEMS feature scales in mind. The die is replicated across the entire wafer, creating a periodic surface layout. Each die contains four arrays of lines with a layout pattern density of 50%. Thus, the line width and line spacing is equal in these regions. The line width and space for the regions are 500, 50, 150, and 300 µm respectively in Arrays I, II, III, and IV. Surrounding the four line arrays are empty field regions with density of 0%. These “down” areas make up a large percentage of the die area; thus, the test mask features may interact with the polishing pad in new ways.

Figure 4. The test die (left) and layout (right). Layout blocks indicate line width/line space as well as local pattern density.
**Process flow and measurement strategy**

Samples were prepared using 6 inch p-type test wafers. In order to use the test mask to create a pattern with field areas down, we pattern the wafer using image reversal resist and plasma etch to produce the array of raised lines. A thin, 500 Å layer of dry oxide is grown before we deposit a 1 µm film of undoped polysilicon. The thin oxide layer aids film thickness measurement. A cross section appears in Figure 5.

After film deposition, we polish five different wafers using a Strasbaugh 6EC Chemical Mechanical Polisher. We set the down force to 68.95 kPa (10 psi) and the back pressure to 55.16 kPa (8 psi). The table speed is set to 28 rpm, and quill speed to 20 rpm. Hemisphere SS-25 silica slurry is introduced at a rate of 200 mL/min. Our set of wafers are polished at different times ranging from 10 to 50 seconds, in increments of 10 seconds. A Tencor UV1280 tool is used for optical film thickness measurements.

Measurement points are taken along a central scan through the middle of each array (y = 7.5 mm and 12.5 mm). The points are chosen to replicate a 1-dimensional system and help us evaluate how the different line width and space arrays affect the polishing in a 50% density region. Measurement locations are indicated on Figure 6, for Arrays I thru IV, as well as for the surrounding field areas. We believe the field points to be outside the planarization length of the array features, and give a good indication of blanket removal for our CMP process.

**Model extraction and results**

Using the data collected from our measurements, we use the updated step height density model to estimate how the topography of the die will change through each time step. First, we account for a time bias in the measurements. Our CMP machine requires a ramp-up time, during which the machine is ramping to reach the set-point pressure and speed values. To account for this effect, we summed up all the material removed in both the up and down regions of the wafer.
for each time step (10, 20, 30, 40, and 50 seconds) and found the best fit linear function with respect to time. The linear function relating material removed to time is seen in Figure 7 resulting in a time bias of 5.58 seconds.

After incorporating the time bias, our model extracts a blanket removal rate of 2826.3 Å/min, and a planarization length of 3.20 mm. The root mean square error between the model fit and measured data is 254.8 Å. The measurement and model predictions for remaining film thickness are shown in Figure 8.

With the extracted model parameters, we simulate the remaining film thickness for all points on the die. Using the initial conditions of film thickness and step height, we examine what the overall die topography will look like at each time step. In Figure 9, we show the topography of the die after 10 and 50 seconds of polishing. As expected by the step height pattern density model, the corners of the raised blocks polish more rapidly than the center. A slight depression near the upper middle part of the die is also captured by the model.

Turning again to the measurements shown in Figure 8, we also find an apparent removal rate dependence on the size of the features being polished. While both Array I and Array II have the same local density (50%), the amount of material removed from the up area of Array I is less than the amount removed from the up area of Array II. Conversely, we find more material being removed from the down regions of Array I than from the down regions of Array II. The model fit attempts to find a tradeoff between the two, ending with a predicted remaining film midway between the measured results of the two regions (Figure 8).
We believe this discrepancy occurs due to pad bending across the size of the features in question. Although the step height is still quite large, the pad can bend down and polish more of the down area of Array I. Conversely, the up areas of Array I are polished less than expected. When the die features approach the same order of magnitude as the planarization length (0.5 mm in Array I compared to 3.20 mm planarization length), the pattern density effect and the removal rate function (Figure 3) become intertwined. The pattern density effect no longer averages together the densities of a large number of surrounding features. Instead, it is incorporating a small number of large features. Large feature areas might have appreciable down area polish because the features are spaced so far apart that the pad can bend down, even when the pattern density is the same as small feature areas. The different configuration of density (grouping into large features) on the scale of the planarization length causes different polishing. This suggests future model enhancements that take into account line width, line space, or even the aspect ratio of the features being polished.

**CONCLUSIONS AND FUTURE WORK**

We have presented an experiment to characterize the chemical-mechanical polishing of polysilicon MEMS structures. In the process, we examined past CMP models and applied them to our current experiment. While capturing the primary trends of polysilicon MEMS polishing, our results have highlighted some of the shortcomings of the pattern density and step height density models. We have found that MEMS designs appear to have dependencies upon the pattern density configuration, especially when the density is grouped into large features. As these feature sizes approach the planarization length, the models no longer accurately predict polishing.
In the future, we should consider reviewing the models and incorporating some feature size or aspect ratio dependence. We could also consider analyzing our data with contact wear type models proposed by Chekina [9] and Yoshida [10], or with a model that integrates both contact wear and step height pattern density models proposed by Cai [11]. The impact of pad grooves should also be studied, as these become comparable to the large feature sizes. An extension of this experiment can examine damascene polishing with inlaid polysilicon structures.

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REFERENCES


