

Characterization and Modeling of Chemical-Mechanical Polishing for Polysilicon Microstructures

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Abstract—Long the dominant method of wafer planarization in the integrated circuit (IC) industry, chemical-mechanical polishing is starting to play an important role in microelectromechanical systems (MEMS). We present an experiment to characterize a polysilicon CMP process with the specific goal of examining MEMS sized test structures. We utilize previously discussed models and examine whether the same assumptions from IC CMP can be made for MEMS CMP. We find that CMP at the MEMS scale is not just pattern density dependent, but also partly dependent on feature size. Also, we find that new layout designs relevant to MEMS can negatively impact how well existing CMP models simulate polishing, motivating the need for further model development.

Index Terms—Chemical-Mechanical Polishing, polysilicon, MEMS, CMP, planarization.

I. INTRODUCTION

CHEMICAL-MECHANICAL Polishing (CMP) serves as the dominant method for wafer planarization in the integrated circuit industry. Prediction of post-CMP film thicknesses is crucial for CMP process optimization, pattern density equalization (dummy-fill), and circuit analysis. However, most past work examining CMP has focused on smaller features and die sizes for the ever-shrinking IC industry.

The microelectromechanical systems (MEMS) industry, on the other hand, does not necessarily gain the same benefits from miniaturization. First, mechanical structures might require large features to operate. The feature sizes we examine are orders of magnitude larger than transistor gates. MEMS CMP is confronted by a different set of

material. Second, Integrated circuit CMP models focus on oxide and other inter-layer dielectrics, as well as the polishing of copper interconnects. Our MEMS CMP study examines the polishing of polysilicon, a material used widely in MEMS devices.

A third important difference between IC and MEMS CMP relates to wafer bonding, where planarization for MEMS devices is needed for surface preparation. The bonding of patterned wafers is an enabling technology for many types of MEMS. Fabrication creates die and wafer level features, but also increases surface roughness that can impede bonding; CMP can be used to decrease the surface roughness and can cause previously non-bonding wafer pairs to bond. At the same time, the polishing process will also affect the wafer's structural patterns. CMP provides excellent planarization of individual patterns, but may result in global nonplanarity caused by differences in pattern size or density across the die or wafer.

In order to examine the effects of feature size and density on polish uniformity, we model the CMP process using an analytical model proposed by Stine et al. [1]. This model uses test masks and patterns to characterize model parameters for a given CMP process. The model produces analytical solutions for polishing based on effective pattern density across the target die [2]. Also central to this model is the idea of planarization length. Planarization length incorporates a distance over which the CMP process creates local planarization, but fails to remove global nonplanarity. The step height density model [3] 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 issues unique to CMP for MEMS structures.

II. REVIEW OF MODELS

A. Pattern Density Model

Proposed by Stine et al. [1], the pattern-density CMP

Manuscript received October 30, 2003. This work was supported by the Singapore-MIT Alliance under (get Memorandum of understanding number and office title, etc.

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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), which relates the polishing of features to pressure P , relative velocity v , and the empirical Preston coefficient k_p .

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

For the pattern density model, the polishing rate applies to areas of raised features, or "up area." 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 the wafer is polished at the blanket removal rate. Up area polishing depends on ρ , 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) . The size of the filter function is called the *planarization length*. The different density filters can take different shapes, such as squares, cylinders, Gaussian shapes, elliptical shapes, and cone shapes with the form of $1/(r+a)^b$. The filter shapes can be seen in Fig. 1. Ouma compared the effectiveness of the different filter weighting functions, and found the elliptical and Gaussian shapes have the best performance [2]. The elliptical and Gaussian shape are thought to give the best performance because they are conceptually close to the physical bending of the CMP pad. Once the filter function shape and planarization length have been selected, the effective density can be easily calculated by multiplying the fast Fourier transforms (FFTs) of the filter function and local density of the wafer.

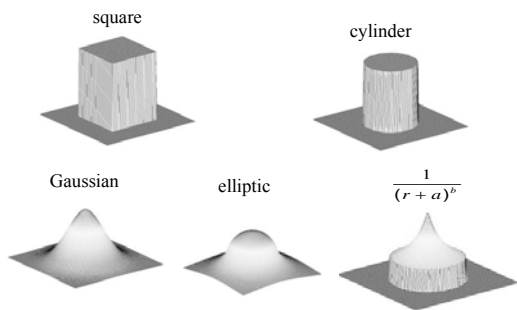


Fig. 1. Effective density weighting functions.

B. Step Height Density Model

Although the pattern density model describes 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 [3]. 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 Fig. 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 for both the up and down areas changes. We model the change in removal rate as a linear function of step height. 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.

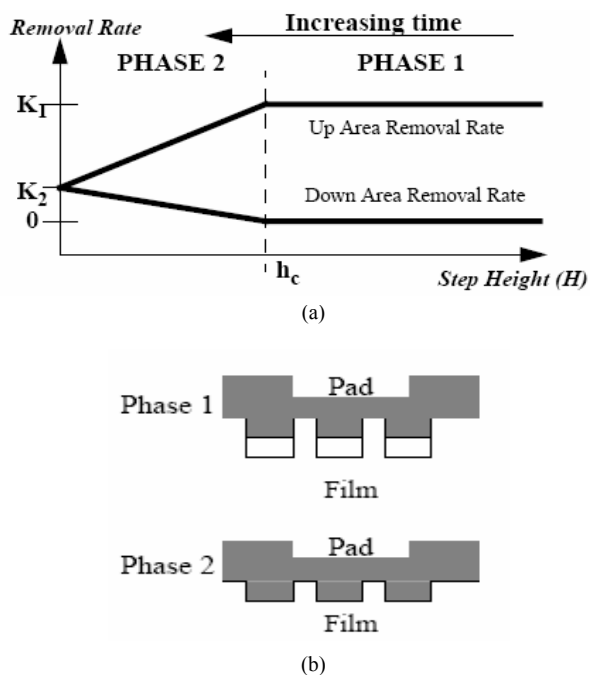


Fig. 2. (a) Step height removal rate dependence. (b) How the pad contacts the film in the two different phases.

III. CMP CHARACTERIZATION EXPERIMENTS

A. Characterization Test Mask

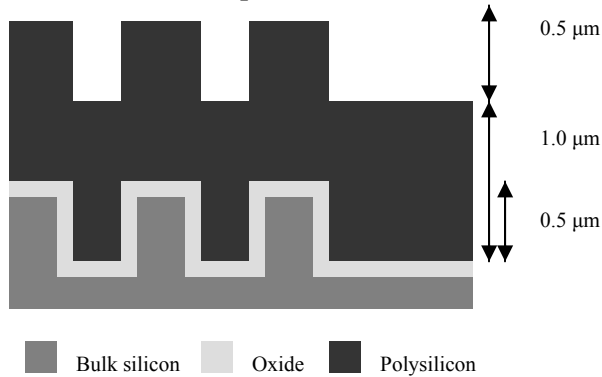
The test mask used was designed with MEMS features scales in mind. The die is replicated across the entire wafer, creating a fully periodic surface layout. It contains four arrays of lines with overall pattern density of 50%. Thus, the line width and line spacing is equal in these regions. The line width and space for the regions are 500, 50, 150, and 300 μm respectively. Surrounding the four line arrays are empty field regions with density of 0%. These "down" areas provide a new way to examine CMP, because they make up such a large percentage of the die area. Past CMP test masks have generally consisted primarily of "up" regions with smaller areas of down

Test Die Layout

0%	0%	0%	0%	20mm
0%	500/500 50% Array I	50/50 50% Array II	0%	
0%	150/150 50% Array III	300/300 50% Array IV	0%	
0%	0%	0%	0%	
				5mm

(a)

Sample Cross Section



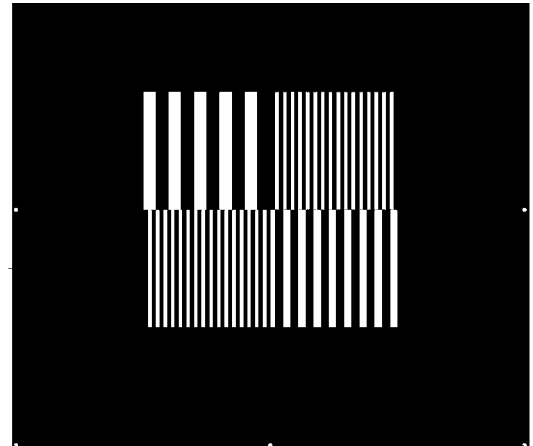
(b)

Fig. 3. For the four array zones, the number a/b is line width/line space in microns. The second number is a density percentage. The final line is the name of the line array. If the block has a 0%, then it represents a down region. (a) CMP test mask layout. (b) Cross section of line array abutting a field region. The step height of the features is $0.5\ \mu\text{m}$, while the total polysilicon film thickness is $1.0\ \mu\text{m}$. The thin oxide layer is only $500\ \text{\AA}$ thick

regions. Thus, the new test mask features may interact with the polishing pad in new ways. The layout of our test die, as well as a sample cross section can be seen in Fig. 3.

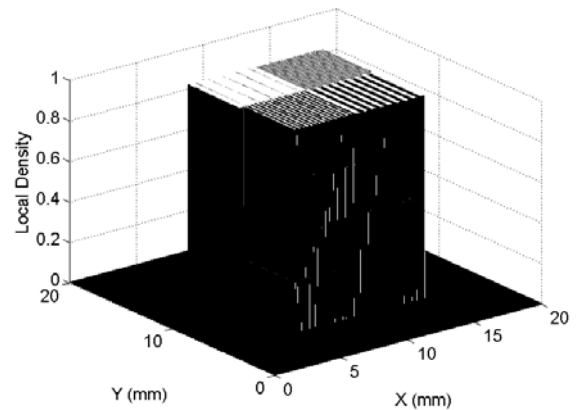
From the mask layout, we calculate local density by averaging the “up” density within $40\ \mu\text{m}$ by $40\ \mu\text{m}$ discrete cells. The local density map and the planarization filter function are convolved to create the effective density map. To save computation time, and to take advantage of the periodicity of the dies on the wafer, we use the Fast Fourier Transform (FFT) technique to quickly produce the effective density mask. While the assumption of periodic die on the wafer allows FFT use, we must decide how to deal with die on the wafer edge, where the wafer map is no longer periodic. The dies in these locations will have very

Test Die



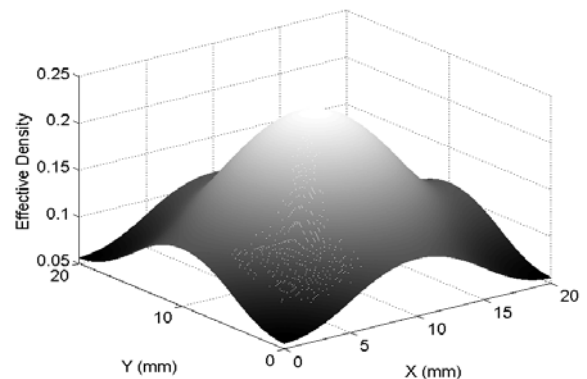
(a)

Local Density Profile



(b)

Effective Density Profile

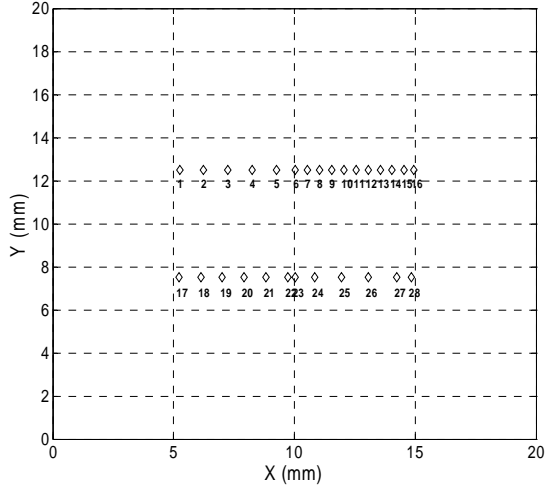


(c)

Fig. 4. (a) Mask layout. (b) Local density profile. (c) Effective density profile.

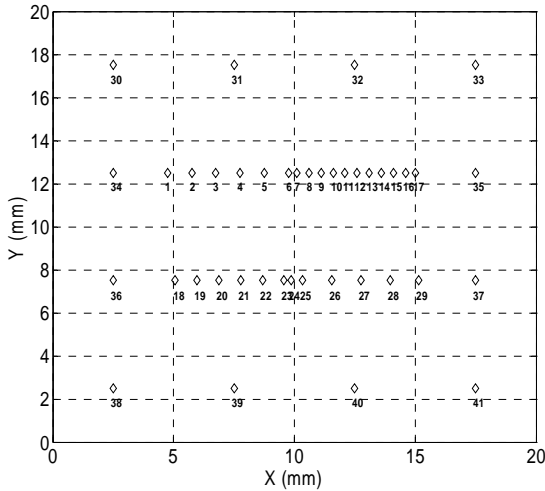
different polishing characteristics in relation to dies near the middle of the wafer. Rather than include the dies that

Up Area Measurement Sites



(a)

Down Area Measurement Sites



(b)

Fig. 5. (a) Locations where we measure film thickness for up regions. (b) Locations where we measure film thickness for down regions.

lie in the edge exclusion zone, we simply discard the outermost die, and instead focus on dies that don't suffer from wafer edge effects. Fig. 4 shows the effective density of our test die using a Gaussian filter function with planarization length of 0.7 mm.

B. Sample preparation and process flow

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 first patterned the wafer using image reversal resist and plasma etched to produce the array of raised lines. A thin, 500 Å layer of dry oxide was grown before we deposited a 1µm film of undoped polysilicon.

TABLE I
EXTRACTED PLANARIZATION LENGTHS AND RMS ERRORS

MODEL	POLISH TIME (s)	PLANARIZATION LENGTH (mm)	UP RMS (Å)	DOWN RMS (Å)
Density	10	14	4159	168.5
Density	20	5.9	3536	282.9
Density	30	0.5	2368	341.3
Density	40	8.3	2838	409.8
Density	50	13.9	2598	485.0
Step Height	10	0.7	160.3	189.4
Step Height	20	0.7	286.1	345.6
Step Height	30	0.7	365.7	415.6
Step Height	40	0.7	377.2	514.3
Step Height	50	0.7	393.2	574.2

The thin oxide layer was included to aid film thickness measurement.

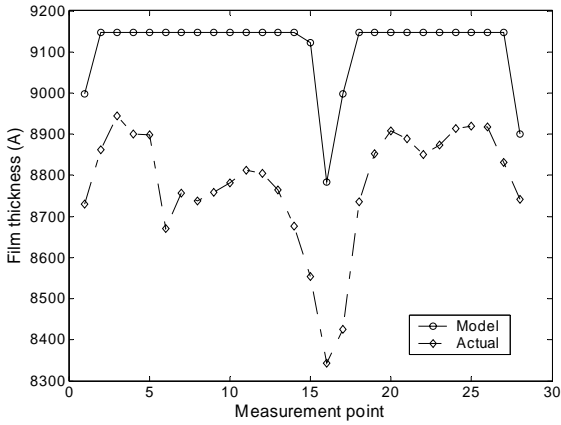
After film deposition, we proceeded to polish five different wafers using the Strasbaugh 6EC Chemical Mechanical Polisher. We set the down force to 68.95 kPa (10 psi) and the back pressure to 55.16 kPa (8 psi). The Table speed was set to 28 rpm, and the quill speed set to 20 rpm. The CMP process used Semisphere SS-25 silica slurry introduced at a rate of 200 mL/min. Our set of wafers was split up and polished at different times ranging from 10 to 50 seconds, incremented by 10 seconds.

C. Measurement Tools and Strategies

To characterize the polysilicon CMP process, we measure the film thickness before and after polishing. Optical film thickness measurements were taken with a Tencor UV1280 film thickness measurement system.

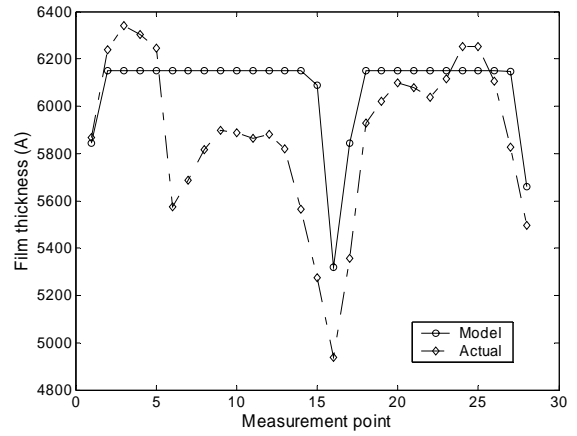
Measurement points were taken along a central scan through the middle of each array ($y = 7.5$ mm and 12.5 mm). The points were chosen to replicate a 1-dimensional system and help us evaluate how the different line width and space arrays affect the polishing in a 50% density region. We also took data measurements evenly spaced through the field regions around the raised line arrays. Measurement locations are indicated on Fig. 5. Array I contains up measurements 1-5 and down measurements 1-6. Array II contains up measurement sites 6-16 and down measurement points 7-17. Array III contains sites 17-21 for up measurements and sites 18-23 for down area measurements. Array IV holds all the remaining up area measurement points, 22-28. It also contains down measurement points 23-29. Down area measurement sites 30-41 exist in the empty field regions surrounding the

Up Area Film Thickness After a 10 Second Polish



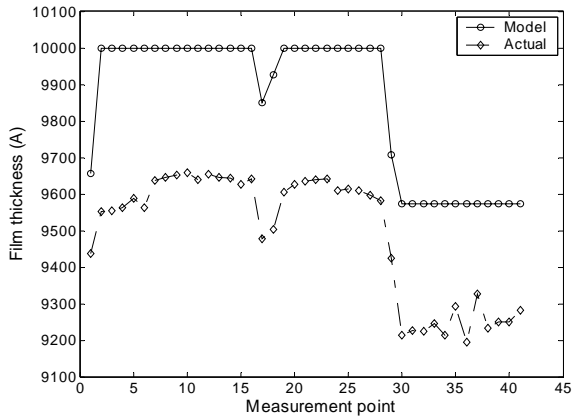
(a)

Up Area Film Thickness After a 50 Second Polish



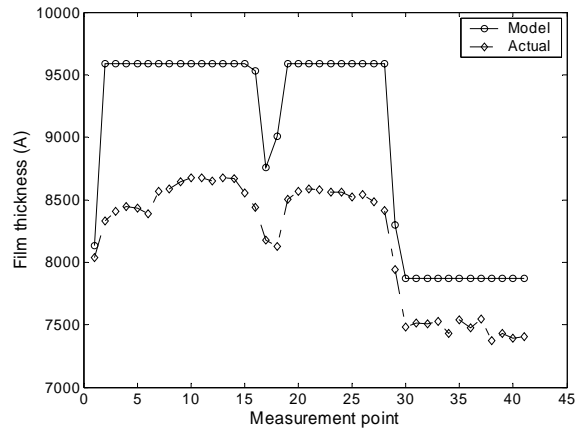
(a)

Down Area Film Thickness After a 10 Second



(b)

Down Area Film Thickness After a 50 Second



(b)

Fig. 6. A comparison of the measured and predicted thicknesses after a 10 second polish for (a) up areas, and (b) down areas.

Fig. 7. A comparison of the measured and predicted thicknesses after a 50 second polish for (a) up areas, and (b) down areas.

raised line arrays. We believe the field points would be outside the planarization length of the array features, and give a good indication of blanket removal for our CMP process.

IV. MODEL EXTRACTION AND RESULTS

We utilized both the effective density and step height density models to extract CMP process parameters from our test data. Because we time multiplexed across wafers, we can extract process parameters from each sample. The planarization lengths, blanket removal rates, and errors are shown in Table I.

We find that the step height model produces less error than the effective density model. We expect this result because the large feature on our test mask allow for pad compression, bringing the pad into contact with down areas of each die. The Effective Density Model assumes that all up areas are polished before the wafer is blanket

polished. Thus, the step height must be reduced to zero before any down areas get polished. But from our data, we find that down regions in the field get polished from the start. Therefore, the assumption of the effective density model does not hold, and the results for our test mask reflect the model's shortcomings. However, the error for every test case for the step height density model is also high. These errors might be attributed to the large amounts of down area in each die. Using the extracted model parameters with the least total error, we can compare the actual and expected film thicknesses in Fig. 6 and Fig. 7.

The large field areas can make discovering the correct contact height difficult. When dies are arranged side by side, there will be a 10 mm by 10 mm area with zero percent density. These dimensions are much longer than the extracted planarization length, leading us to believe that field regions are polished from the moment the head brings the wafer in contact with the pad. Because this down region immediately contacts the pad, the contact height of

Effective Density Contour Plot

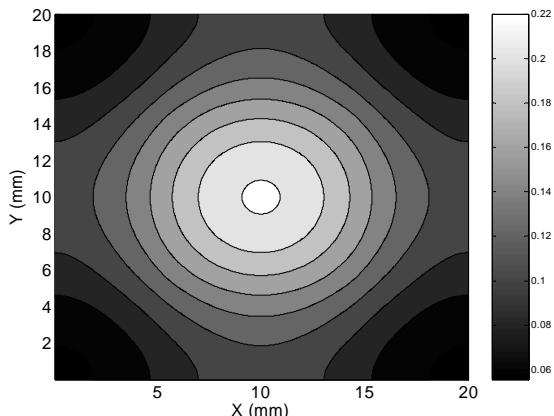


Fig. 8. Effective density contour plot of the test mask with a planarization length of 0.7 μm .

the pad must be larger than the initial step height of 0.5 μm .

Another driver of down area error could be the large feature sizes. Fig. 6 and Fig. 7 both show that the line array with the least up area polishing also has the most down area polish. This difference is best seen in the 500 μm line width area and the 50 μm line width area. The up regions for the smaller line width (up points 6-16) are polished a lot compare to the up regions of the large line width (up points 1-5). The large line width areas undergo less up area polish because large portions of the pad can bend down and come into contact with the corresponding down regions (down points 1-6). Therefore, the pad pressure spreads over a larger area, decreasing polish rate. With the small line widths, the pad cannot bend down and contact the down regions (down points 7-17) as much. Thus, the majority of the pad pressure focuses on the up regions, leading to more polishing of up structures and less polishing of down structures. Even though the two regions have the same up local density, their polishing characteristics differ. In addition to local pattern density, the effective density of the two regions is nearly identical, as seen in Fig. 8. Because these regions with the same local and effective pattern density have different polishing characteristics, we must conclude that feature size affects polishing for the larger structures we see in MEMS.

V. CONCLUSION 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 material set. Our results have highlighted some of the shortcomings of the pattern density and step height density models, specifically dealing with our mask design. In the future, we should consider reviewing the models and incorporating some feature size dependence. We could also consider analyzing our data with contact-wear type models proposed by Chekina [4] and Yoshida [5]. An extension of this experiment can

examine the characteristics of longer polishes where the polysilicon film becomes inlaid within the substrate.

ACKNOWLEDGMENT

The authors would like to thank the Singapore-MIT Alliance (SMA) for providing the financial support for this research. We also would like to thank all the staff at the MIT Microsystems Technology Laboratories for their help and guidance with fabrication and testing. In particular, we would like to thank X. Xie, T. Park, and members of the Statistical Metrology group for their valuable assistance with polish models.

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