A Two-Dimensional Process Model for Chemi-Mechanical Polish Planarization

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As device sizes are scaled to sub-micron dimensions, planarization technology becomes increasingly important, both for bipolar and CMOS trench isolation and for multi-level interconnects and wiring. Although chemi-mechanical polishing (CMP) has been used extensively in silicon technology for wafer preparation[1,2], it is only recently that CMP has emerged as a new technique for achieving a high degree of planarization during VLSI processing. One example has been the application of CMP to the fabrication of sub-micron lithography-limited trench isolation[3-5]. The key aspect of CMP is that it is an implicitly non-local process, so that the removal or polish rate at a given point is determined by the topography and the relative heights of the surrounding features. In this way, a degree of planarization can be achieved which is superior to that obtainable by more conventional techniques. However process design can be difficult, since the effects of the polishing will depend on the device layout and the local pattern density. It is thus crucial to develop a model of the CMP process which will allow a full exploitation of the power of this technique, but to date, little has been reported on this subject. Here we describe a relatively simple two dimensional model which, with only 3 adjustable parameters, succeeds in predicting both relative and absolute polish rates for arrays of features under different polishing conditions. The model is extendable to three dimensions, and is also applicable to preferential or selective polishing processes[6,7].

The model treats CMP in an empirical way, using 3 adjustable parameters to describe the characteristics of the polishing pad and some of the kinetic factors involved in the process. The parameters represent a length scale in the horizontal (x) direction, a vertical (z) length scale related to the fuzziness of the pad, and a horizontal polish rate associated with the motion of the pad across the surface. The x length scale determines the range of influence of a given topographical feature, and the z length scale determines the magnitude of that influence for a given feature height. To model the polishing of a specific array of shapes, a two dimensional matrix of points was used, and for each point "i" in the matrix, an influence factor is calculated based on the surrounding topography. Exponential functions were used to describe the shading effects of neighboring points which protrude above point "i", hence decreasing the polish rate around point "i". In particular the following form was used; $S_i = \exp\left(\frac{\Delta z_i}{z_0}\right)$ where the polish rate at point "i" is decreased by the factor S_i, and the model parameter z_0 represents the characteristic vertical length scale. The quantity $\overline{\Delta z_i}$ is calculated by averaging over the regions where the product $\Delta z W(x)$ reaches its maximum values, where Δz is the relative elevation between the surrounding points and point "i", and x is the horizontal separation. W(x) is a decaying function incorporating the characteristic x length scale, describing the fact that points which are far away from "i" tend to have little influence on the polishing rate. For physical reasons, W(x) should be such that it has no cusp at the origin. The following form was thus chosen for W(x) (decaying exponentially at large distances); $W(x) = [\cosh(\frac{x}{x_0})]^{-1}$ where x_0 is the characteristic x length scale. For every point whose polish rate is decreased by the effect of an elevated neighboring feature, the model assumes that there will be a corresponding point or points elsewhere whose polish rate is increased by the same amount. In general a given point will simultaneously shade some points while being shaded by others, necessitating a self consistent solution for the whole matrix. Finally, kinetic effects are included by assuming a horizontal polish rate (the third model parameter) and calculating the component in the direction normal to the surface at every point.

To test the predictive powers of the model described briefly above, a thick oxide layer on a silicon wafer was partially etched, leaving an array of elongated oxide shapes of regular width and spacing, illustrated schematically in fig 1). The wafer was then polished in several stages, with the total removal after each stage measured in a region remote from the oxide shapes. The profile of the array after polishing was measured with a sub-micron stylus scanning instrument, and the digital data were collected and used as a comparison to the modeling results. The results are shown in figure 2 a), at different stages in the polishing process, and the model results are shown in figure 2 b). The model successfully predicts both the absolute polish rate of the features in the array, and also the rounding which occurs in the polishing process. An x length scale of 4.2 microns and a z length scale of 20 nm were found to provide a satisfactory fit to the data.

Changing the polishing conditions (in particular increasing the hardness of the polishing pad) was demonstrated to provide improved planarity, as expected. Figure 3 shows both experimental and modeled results under these conditions. In this case, an x length scale of about 40 microns is required to describe the data. Thus the model provides a quantitative description of the polish process under these conditions and provides a basis for comparison and optimization of the process.

Finally, the model was applied to a selective process, where two materials with different polish rates are simultaneously polished. In this case the features are formed by patterning a silicon nitride film on a thick blanket oxide film as shown in fig. 4a). The resulting structure is then polished and measured as before with the stylus. The measured oxide and nitride polish rates are used as inputs to the model, along with the same model parameters used for the results shown in fig. 2b). Both model and experimental results are shown in fig. 4b). It is interesting to note that under these conditions, the polishing results in an increase of the topography present, since the nitride is removed more slowly than the oxide. The close fit between model and experiment demonstrates the validity of the model under these conditions.

A mathematical formulism has been developed which successfully describes CMP in a quantitative way, providing a real basis for detailed process modeling. Extension of the model to three dimensions is straight forward in principal, although the data collection and analysis becomes more difficult. The utility of such a model is not limited to just CMP for trench and isolation processing, but should be relevant to more general applications as well. Furthermore, this quantitative measure of the various relevant length scales allows the CMP process itself to be optimized for a particular application. Models of this type will be indispensable for future generations of VLSI technology which will rely more heavily on CMP processes.

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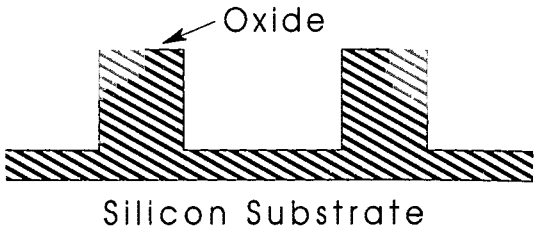
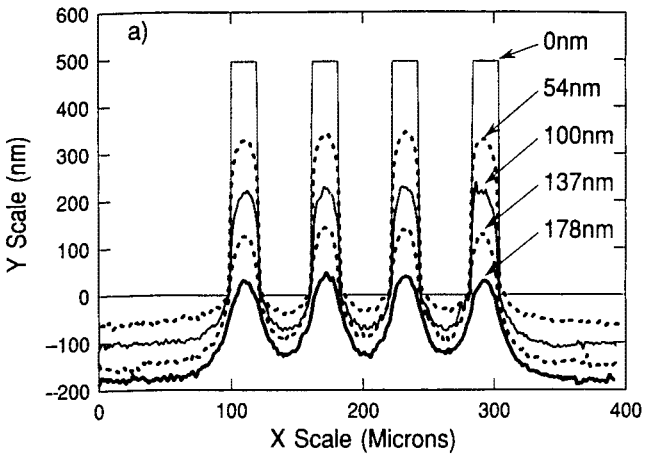
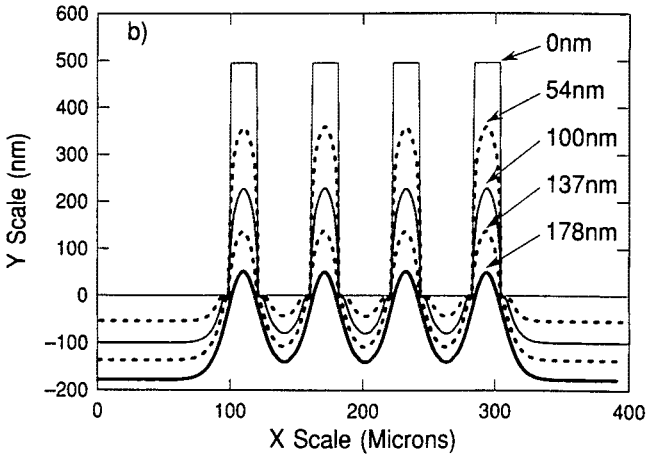


Figure 1. Oxide structure for polish model experiments.



a) Experimentally measured polished profiles.



b) Model results for the same array as in a) after polishing the same amounts.

Figure 2. Experimental (part a), above) and model results (part b), above right) for the polishing of an array consisting of 20 micron wide lines with 40 micron spaces, polished in successive steps. The amount of material removed from the field regions is as indicated.

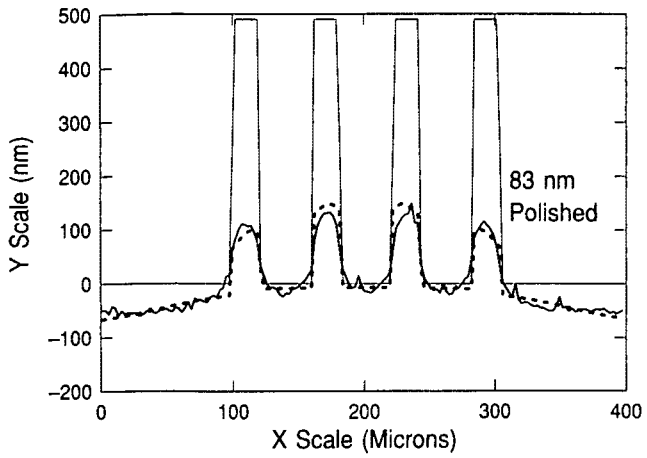


Figure 3. Polishing of oxide structures, the same array as in fig. 2 with a harder pad. Thin lines show the unpolished shapes, solid dark line is the array after polishing, and dashed line is the model prediction.

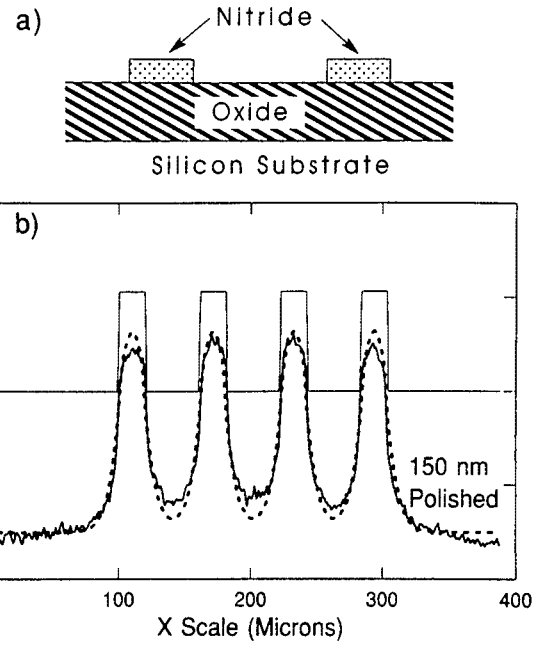


Figure 4. Polishing of nitride/oxide structures a) Schematic cross section. b) Comparison of model result with experimental result. Line types as in figure 3. Material above the reference line Y=0 is nitride, below Y=0 the material is oxide.