CHAPTER 7

SUMMARY

In general, CMP process requirements fall into two categories: geometry and the rate of material removal. Ideally, the CMP process must remove excess material and maintain a flat, smooth surface within each die area. However, due to the uncertain wafer/pad interfacial contact conditions, the pattern layout within the die, and the dimensions and geometry of surface features, surface nonuniformity sometimes exceeds the specifications required to integrate with lithography, deposition, and other fabrication processes. This thesis developed models related to the causes of surface nonuniformity. Based on different length scales, three nonuniformity problems in CMP were addressed: wafer-level nonuniformity, die-level nonplanarity, and device-level topography (dishing and overpolishing). Chapter 2 correlated the wafer-level nonuniformity with the contact condition at the wafer/pad interface. Three contact regimes: direct contact, hydroplaning, and mixed mode, were examined for the CMP process. Models relating the friction coefficient to process parameters such as pressure, velocity, and slurry viscosity were established to characterize the contact condition. The experimental results in this thesis showed that typically the friction coefficient is around 0.1 for the contact mode, of the order of 0.01 to 0.1 for mixed mode, and about or less than 0.001 for the hydroplaning mode. The results also suggest that the CMP process must be operated in the contact mode. Mixed and hydroplaning modes are not stable process modes. In these modes, the material removal rate may vary across the wafer surface due to the nonuniform pressure distribution at the partial contact interface or within the fully developed slurry fluid film, due to the fluctuations in slurry flow.

Chapters 2 and 3 addressed the effects of process parameters on the MRR. The Preston constant is only independent of the pressure and velocity in the contact regime. After the transition point, the Preston constant decreases as the relative velocity increases and nominal pressure decreases. The Preston constant is highly correlated with the friction coefficient. Thus, in practice the friction coefficient can be monitored to operate the process in the contact mode for high, uniform MRR. Theories of polishing processes -- surface melting, plastic deformation, brittle fracture and burnishing – were reviewed and examined by the CMP experimental results to determine the dominant mechanisms of material removal. The prevailing mechanism of material removal in fine abrasive polishing is plastic deformation. The effects of the hardness of coating materials, the abrasive size, and the pad stiffness on the MRR and Preston constant were studied. The MRR, NMRR and Preston constant are inversely proportional to the hardness of the coatings. This results in a high selectivity in Cu polishing between the soft Cu/barrier metals and ILD oxide and dishing of the Cu surface. The experiments also showed that MRR increases with the increase of particle size, yet the surface roughness and scratching still remain at a desired low level. The particle size and abrasive hardness might be selected to enhance MRR in Cu polishing while maintaining low surface roughness.

Chapters 4 and 5 presented models for die-level nonplanarity and dishing and overpolishing in Cu CMP. On the basis of contact mechanics modeling, the die-level nonplanarity was related to the nonuniform pressure distribution on the surface of different pattern structures. Because the pad displacement into the low features for sub-micron lines is very small and insignificant compared with surface roughness, the load is carried mostly by the high features in the planarization regime. Therefore, the planarization rate increases with the area fraction of Cu interconnects (i.e., the area fraction of the low features). Additionally, the pad displacement increases with the linewidth and decreases with the increase of pad elastic modulus. For a broader line or a pattern structure polished faster than the adjacent area, the pad may contact the low surface and slow down planarization. The contact mechanics models also provide a quantification tool to evaluate and choose the optimal pad stiffness so that the surface topography can be retained at a desired level. Moreover, Cu dishing and oxide overpolishing were studied. A steady-state, semi-empirical model for the pattern evolution in the overpolishing regime was proposed. The amount of dishing increases with linewidth of the Cu interconnections. For submicron features, less than 0.5 μm, the Cu dishing reaches a small steady-state value, comparatively insignificant to the overall surface nonuniformity, within a short period of overpolishing. On the other hand, the oxide overpolishing increases with time and is mainly affected by the area fraction and the hardness of the coatings. An “apparent hardness” determined the overpolishing rates on patterns with different area fractions. Both the contact mechanics model and the overpolishing model not only explain the mechanisms of planarization, dishing and overpolishing, but also provide a tool for predicting the pattern evolution in Cu CMP and designing pattern layout to achieve better polishing uniformity.

In addition to the fundamental understanding of the CMP process, both the analytical and experimental results were employed for the design of process optimization schemes. To enhance the MRR, the pressure-velocity product and the Preston constant must be optimized. The optimal v_R/p ratio can be determined based on contact condition and frictional heat generation. It is possible to increase the MRR and Preston constant by increasing the abrasive particle size or by the chemical-mechanical approaches, such as using moderately acidic slurry. In addition to increasing MRR, it is also important to retain the within-wafer uniformity, within-die planarity, dishing, overpolishing, surface roughness and scratching at acceptable levels. Optimization schemes, such as increasing the pad stiffness, choosing the right pressure-velocity regime, and designing the macrostructure of the pad to improve slurry dispensing, are proposed to reduce the WIWNU and within-die planarity. Proper abrasive size and hardness can be selected and the slurry chemistry tailored to increase the selectivity between Cu and the ILD oxide to retard overpolishing at the onset of endpoint. Similarly, surface roughness and scratching may be reduced by using a fine-grade abrasive, by narrowing the abrasive size distribution, and by designing the pad micro- and macro-structures to reduce abrasive agglomeration.

Finally, Chapter 6 developed an *in situ* reflectance sensing technique to detect the polishing uniformity and endpoint for the Cu CMP process and to account for both systematic and stochastic variation of the process parameters. An analytical model for the effect of surface topography and the area fraction of Cu on the reflectance of a patterned surface was developed. The kinematics of the sensor was studied and its trajectories on the wafer were designed to gain the information on spatial resolution, both global and local. Experiments were conducted to verify the detection schemes and the capability of the reflectance sensor. Based on the results, metrics for detecting process endpoint, such as mean, variance, range and the distribution of the surface reflectance, were developed and their applicability was examined by experiments. The ratio σ/μ, the ratio of the standard deviation to the mean reflectance, can effectively determine both the global and the local endpoints. This ratio reaches a minimum when the endpoint is achieved, no matter what the structure is. Combined with the robust process design and optimization schemes, the *in situ* sensing and endpoint system provides a means to ensure the production quality and provide information for more advanced process control for improving run-to-run uniformity and yield.