ABSTRACT

Smith, Katie Maureen. Ph.D., Purdue University, December 2013. Particle Adhesion in Nano-structured Microelectronics Systems. Major Professor: Stephen P. Beaudoin.

In the microelectronics industry yield is everything, and each year billions of dollars are spent on efforts toward yield enhancement. The integrated circuit (IC) fabrication process oftentimes consists of hundreds of steps, of which many may present situations that can cause a reduction in yield. In particular, the adhesion of contaminant particles to wafer and photomask surfaces is a problem of critical importance to the manufacture of microelectronics since these “killer defects” render wafer dies non-functioning, thereby reducing yield. As expectations for IC dimensions continue to shrink and restrictions on material loss become more stringent, many devices are approaching operating conditions at which one or more of their spatial dimensions are on the same length scale as van der Waals (vdW) forces, the primary forces governing particle adhesion near contact. The physical origins of these forces are described within a field known as quantum electrodynamics (QED), an area of study reserved typically for physicists and not widely tractable among the engineering sciences. Consequently, the microelectronics industry does not have a straightforward theoretical framework to guide the development of new surface processing or cleaning technology.

In this work, we investigate the effect of varying nanoscale surface film thickness on particle adhesion of the vdW type to layered substrates. First, we examine a model system consisting of a silicon nitride atomic force microscope probe, representing a contaminant particle, and a silicon substrate onto which alumina films have been deposited via atomic layer deposition. We then apply theory developed by Vold to describe the effect of the thickness of the surface film material on the vdW interaction force between the particle and substrate. This theory is based on the assumption that each component of the layered substrate has a vdW interaction with the particle, but that the presence of each component does not affect the vdW interaction of the other. Our experimental data reveal that this assumption is appropriate only at the limits of behavior, i.e. for very thin and very thick coatings. To address the deficiencies of the Vold theory, we turn to Lifshitz's formulation—a fully rigorous, QED-based theoretical framework for modeling vdW interaction phenomena—in the form of a simulation module written in the MATLAB language. Per the simulation results for the model system, we conclude that representing the nanoscale surface film as a bulk material is incorrect, and that in fact the properties contributing to its vdW interaction must depend on the thickness of the film itself. Finally, we examine an industrial-scale system involving the removal of exemplar contaminant particles of silicon dioxide from the surfaces of 300 mm-diameter Si wafers with titanium nitride surface films of varying thicknesses. The results from these investigations demonstrate the significant effect that nanoscale surface film thickness has on macroscale particle adhesion and particle removal efficiency.