A Three-Dimensional Photolithography Simulator Including Rigorous Nonplanar Exposure Simulation For Off-Axis Illumination

Heinrich Kirchauer and Siegfried Selberherr
(Institute for Microelectronics, TU Vienna, A-1040 Vienna, Austria/Europe)

Progress in today's semiconductor industry has been mainly achieved by decreasing the minimal feature size and increasing the complexity and thus the nonplanarity of the devices. Therefore lithography tools have to provide high resolution with a reasonable large depth of focus. A well-established method to achieve both requirements are off-axis illumination techniques. As topography effects such as nonplanar electromagnetic scattering and notching are critical for line-width control, a rigorous three-dimensional exposure simulation considering both nonplanar surfaces as well as off-axis illumination is of utmost interest. We will demonstrate a method that meets the two challenges of nonplanar substrates and off-axis illumination.

Our approach is based on a novel extension of the differential method to the third dimension and is thus suited for nonplanar topography. As in our method the Maxwell equations are solved in the frequency domain by expanding the electromagnetic field into Fourier series, the partial differential equations are transformed into ordinary ones. In the thereby obtained discretized linear algebraic equation the incident field is represented by its Fourier coefficients and corresponds to the right-hand side vector. We calculate these diffraction orders by the vector-valued extension of the scalar Fourier optics. Polarization and aberration effects for high-*NA* systems as well as phase-shifting masks can be simulated. To account for oblique illumination we discretize the arbitrary shaped aperture into mutually independent coherent point sources. Like the aerial image the latent bulk image is formed by an incoherent superposition of all point source contributions. This approach is commonly referred to as Abbe's method of imaging. To avoid the separate solution of the Maxwell equations for each point source, we implemented a special aperture discretization algorithm. This algorithm chooses the spacing between the point sources in such a way that all incident field contributions are quasi-periodic with the same phase offset. Due to this specific choice the various excitations result in multiple right-hand sides, i.e., the system matrix describing the inhomogeneous photoresist and the nonplanar parts of the topography has to be calculated just once independent of the number of point sources. The final linear system can then be solved efficiently by employing LU-factorization. The extra effort due to the off-axis apertures is of one order lower than the overall numerical costs and thus negligible.

We can demonstrate that our approach is extremely efficient for the simulation of nonplanar scattering effects under off-axis illumination by describing the theoretical background of the method and by giving simulation experiments including three-dimensional photoresist profiles obtained with a cellular-based development simulation. These results show the influence of various aperture forms, e.g., annular and quadrupole, on the latent bulk image and on the final resist profile for critical parts of a layout like a contact hole or line with minimal feature size lying over a stepped substrate. Furthermore it will be shown that the notching crucially depends on the underlying substrate material by comparing simulations over an oxide step with a silicon step.