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On the solution of inverse problems in semiconductor metrology

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ABSTRACT

The production of an integrated circuit (IC) requires several hundred manufacturing steps which consist of transferring different stencils, or masks, to layers of semiconductor material using, for example, photolithography. Transistors are created by stacking several of these layers. As the size of these structures was reduced with the advent of new technology cycles, it became increasingly important to introduce advanced control techniques at each manufacturing step to guarantee that these features are printed within specified tolerances. Monitoring these dimensions is important and this is accomplished with a set of methods that go by the common denomination of metrology. Instead of measuring the actual patterned structures, many metrology systems measure test structures, or fiducials, usually grating lines or other periodic forms which are printed at different locations on a wafer. Several of these techniques are based on imaging methods using, for example, scanning electron microscopes (SEMs) that produce an image of the feature from which image processing techniques can be applied to recover critical dimensions (CDs).

These critical dimensions are then correlated to aspects of the manufacturing process. While CD-SEM tools are important in production environments they lack the capability of producing detailed profiles unless the wafer is broken to reveal its cross-section, a process that is destructive and therefore not adequate for in-line monitoring. In the past few years, optical metrology systems that can infer these profiles have been developed [1] and several systems are available commercially.

The basic idea behind one family of systems is to use ellipsometry to measure the change in polarization of a ray of light that is shined on the test structures and from these measurements infer the profile. Ellipsometry is commonly used to measure the index of refraction of materials and/or the thickness of thin, planar films. Basically, for a planar interface or film, Maxwell's equations can be solved analytically and the ratio of reflection coefficients for the two fundamental polarizations with respect to the plane of propagation of the beam can be computed. The ellipsometer measures this ratio of reflection coefficients which depends upon the index of refraction of the material in the case of a planar homogeneous sample and, in the case of a thin-film, also on the thickness, which is a geometric parameter. It is conceptually easy to understand how the original technique can be extended to infer other geometric parameters, such as the profile of periodic lines: in this case the ratio of reflection coefficients will depend upon the shape of the profile as well as the index of refraction of each medium.

This “scatterometry” procedure differs from other metrology techniques in that an image of the grating is never formed since this is not an imaging system, instead the shape of the grating is inferred or reconstructed from the signal measured by the ellipsometer. This reconstruction can be done in several ways: (1) by simulating the response of a pre-determined set of profiles, then picking the best candidate using pattern-matching techniques or (2) by parameterizing the profile then inferring the parameters using a non-linear optimization procedure. In both cases, it is necessary to solve the electromagnetic problem using a full-diffraction simulation as the wavelength of the probing radiation is of the order of the dimensions of a grating line section. Because of the necessity to perform full-diffraction simulations, which are computationally demanding, the first reconstruction approach has been preferred in production environments as measurements of multiple sites in every fabricated wafer are required to monitor the manufacturing process. The non-linear optimization approach is deemed very expensive as the profile is found through an iterative procedure which at every step requires the computation of the derivative of a cost function with respect to every parameter that describes the shape. Usually this derivative is computed using a finite-difference approximation and thus the computational cost grows linearly with the number of parameters. Nevertheless, approach (2) offers advantages as a shape is found automatically, without bias, while in (1) proper care has to be exercised when generating the library to ensure that all possible deviations in the profile due to changes in manufacturing conditions are accounted for.

In this talk, an alternative approach is presented. The reconstruction problem is posed as an optimization problem as in approach (2) but gradients are computed efficiently using adjoint equations. As a consequence, the number of computations required at each iteration is only two: one for the diffraction problem, or forward problem, and the other for the adjoint problem which is shown to have the form of another diffraction problem. Furthermore, if the profile is symmetric, the number of computations is reduced even further as the adjoint problem does not need to be computed under certain conditions.

REFERENCES

[1] X. Niu, N. Jakatdar, J. Bao and C. J. Spanos, “Specular spectroscopic scatterometry,” *IEEE Trans. Semicond. Manuf.* **14**, 97-111 (2001).