Defining Lithographic Quality

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Improving quality in manufacturing is a continual process. Like reducing costs and improving productivity or throughput, quality improvements benefit everyone from the customer to the manufacturer. How can lithographic quality be improved? One of the foundational tenets of quality management is this: before quality can be systematically improved, it must be numerically measured. Just looking at a SEM picture of a photoresist profile and saying "yes, the quality has improved" is not good enough. Numerical metrics of quality must be defined, directly related to customer benefits, and then measured before they can be used to systematically improve your lithography.

So how is lithographic quality defined? This simple question has a surprisingly complex answer. Lithography is such a large component of the total manufacturing cost of a chip and has such a large impact on final device performance that virtually all aspects of the lithography process must be carefully considered. Although somewhat arbitrary, I have divided lithographic quality into four basic categories: photoresist profile control, overlay, downstream compatibility, and manufacturability.

Photoresist Profile Control is a superset of the common critical dimension (CD) control metric that is universally thought to be the most important aspect of high-resolution lithography processes. For many lithographic steps the ability to print features at the correct dimensions has a direct and dramatic influence on device performance. It is typically measured as a mean to target CD difference for one or more specific device features, as well as a distribution metric such as the standard deviation. Spatial variations across the chip, field, wafer or lot are also important and can be characterized together or individually. In addition, the sensitivity of CD to process variations is often characterized and optimized as a method to improve CD control. Metrics such as resolution, depth of focus, and process latitude are expressions of CD control. For example, resolution can be defined as the smallest feature of a certain type that provides adequate CD control for a given process.

Profile control, however, recognizes that the printed resist patterns are three-dimensional in nature and a single CD value may not be sufficient to characterize their lithographic quality. Extension of CD control to profile control means taking into account other dimensions. In the "z direction" from the top to the bottom of the photoresist, the resist profile shape is usually characterized by a sidewall angle and a final resist height. In the "x-y direction" patterns more complex than a line or space require a shape characterization that can include metrics such as corner rounding, line-end shortening, area fidelity, line edge roughness, or the critical shape difference.

Overlay is the ability to properly position one lithographic level with respect to a previously printed level. In one sense, lithography can be thought of as an effort to position photoresist edges properly on the wafer. But rather than characterize each edge individually, it is more convenient to correlate two neighboring edges and measure their distance from each other (CD) and the position of their midpoint (overlay). One simple reason for this division is that, for the most part, errors that affect CD do not influence overlay, and vice versa (unfortunately, this convenient assumption is becoming less and less true as the target feature sizes shrink). Overlay is typically measured using special targets optimized for the task, but actual device structures can be used in some circumstances. Since errors in overlay are conveniently divided into errors influenced by the reticle and those influenced by the wafer, measurements are made within the exposure field and for different fields on the wafer to separate out these components. While historically CD control has gained the most attention as the limiter to feature size shrinks, overlay control may soon be as critical or even more so.

Downstream Compatibility describes the appropriateness of the lithographic results for subsequent processing steps, in particular etch and ion implantation. Unlike many other processing steps in the manufacture of an integrated circuit, the handiwork of the lithographer rarely finds its way to the final customer. Instead, the true customers of the lithography process are the etch and implant groups, who then strip off those painstakingly prepared photoresist profiles when finished with them. Downstream compatibility is measured with such metrics as etch resistance, thermal stability, adhesion, chemical compatibility, strippability, and pattern collapse.

Manufacturability is the final, and ultimate, metric of a lithographic process. The two major components of manufacturability are cost and defectivity. The importance of cost is obvious. What makes this metric so interesting, and difficult to optimize, is the relationship between cost and other metrics of lithographic quality such as CD control. While buying ultra-flat wafers or upgrading to the newest stepper platform may provide an easy improvement in CD and overlay performance, their benefit may be negated by the cost increase. It is interesting to note that throughput (or more correctly overall equipment productivity) is one of the major components of lithographic cost for a fab that is at or near capacity due to the normal factory design that places lithography as the fab bottleneck.

Defectivity in all areas of the fab has been the major contributor to yield loss for most processes throughout the history of our industry. Because lithographic processes are repeatedly applied to make a chip, any improvements in defectivity in the lithography area are multiplied many times over. Finally, concerns such as safety and environmental impact will always play a role in defining the overall manufacturability of a process.

The outline for defining lithographic quality presented above gives a flavor for the complexity of the task. Literally dozens of quality metrics are required to describe the true value of a lithographic result. However, once these metrics have been defined, their relative value to the customer evaluated, and methods for their measurement established, they become powerful tools for the continuous improvement required to remain competitive in semiconductor manufacturing.