Specifying and Measuring Photomask Critical Dimensions

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As users of photomasks for semiconductor IC production, we would like to think of our masks as perfect representations of the design information that we provided to the mask shop. Of course, any major problems with the mask (such as a killer defect) will be caught sooner or later, and repaired or replaced. But other, smaller problems with the photomask may go unrepaired, or unnoticed. In particular, how well are errors in the critical dimensions on the mask measured, characterized, and controlled? How do these errors affect your lithographic performance? How should you specify a photomask so that the critical dimension errors on the mask produce a known, acceptable level of errors on the wafer?

The SIA Roadmap shows that the required mask critical dimension (CD) uniformity scales linearly with the minimum feature size. Thus, each generation of device design requires improved CD control on the mask. This scenario, however, is overly optimistic. For the next several device generations (down to 100nm and probably below), optical lithography will be pushed to accomplish the required resolution by, among other things, lowering the k_1 factor (the resolution scaled by the imaging numerical aperture divided by the wavelength). An important and recently studied impact of lower k_1 imaging is an increase in the mask error enhancement factor (MEEF): the wafer CD error divided by the mask CD error (scaled to wafer dimensions by the magnification). As we have seen in this column before (*MLW, Winter 1999*), as k_1 drops below about 0.5 under typical conditions, the MEEF rises considerably. Since the actual required CD uniformity on the mask is the mask contribution to wafer CD uniformity divided by the MEEF, an increasing MEEF means that CD uniformity must improve significantly faster with each device generation than originally anticipated.

Are current industry practices for mask CD specification and measurement adequate for meeting today's and the future's need for CD uniformity across the mask? Historically, defects have been the major yield limiter in photomask production. Consequently, enormous effort has been put into measurement, reduction, and repair of mask defects. Efforts into CD measurement were limited by their relative lack of importance. However, the increasing need for better CD uniformity means that more and more masks are failing due to CD performance failure. In addition, since CD errors are not repairable, it is anticipated that mask CD performance will increasingly become the main limiter to photomask yield. As a consequence, a complete review of the current approach to CD measurement on the photomask, and its impact on the control of CD uniformity, is required.

Photomask CD specifications are broken up into two categories: mean-to-target CD errors (the difference between the average of all the CD measurements made on the mask and the target CD), and the CD uniformity (the standard deviation of all the CD measurements made on the mask). The fundamental problem with current photomask CD measurement methodologies is the lack of understanding of the very different impacts of mean-to-target CD error and CD uniformity on wafer lithography. Quite simply, mean-to-target CD errors are, for the most part and within a certain range, correctable during wafer lithography while CD uniformity errors are not. If the mean-to-target CD error of a particular reticle is known, this knowledge can be used to modify the exposure dose for that reticle to bring the wafer mean CD into specification. (Incredibly, the SIA roadmap allows CD uniformity errors to be up to twice as large as mean-to-target CD errors!) Thus, the astute mask user requires precise *characterization* of mean-to-target CD error and precise *control* of the CD variation across the mask. This subtle but important difference from current CD measurement philosophy drives an incredibly important change in mask making philosophy: *CD errors must change from being a property of the mask to being a property of the mask making process*. This change can be addressed in the following ways:

- Current CD measurement sampling plans are geared toward determining whether a particular mask plate meets a given set of CD specifications. Not only are the measurement and sampling approaches inadequate, but so are the very nature of the mask CD specifications. The emphasis on tight mean-to-target CD errors versus CD uniformity errors drives some strange behavior in mask production. For example, the common industry practice of iterative CD measurement and development enables a given mask to meet a mean-to-target CD specification at the expense of CD uniformity. Since CD uniformity is so poorly measured on product masks, this problem remains largely unnoticed.

- Special CD measurement test structures used on a product mask can induce systematic measurement errors that produce an offset between the mean-to-target CD error measured on the test structures and the actual mean-to-target CD error of the real mask structures. Also, the uniformity of the structures used for measurements means that systematic errors such as proximity effects and linearity failure are not measured. Further, the CD uniformity measured with these test structures can be systematically better than the actual CD uniformity. This can be caused, for example, by using test structures unlike the actual device structures, and by grouping the test structures in the mask design data. This separate grouping can lead to a grouping of the time of mask writing of these structures, so that any drift in the CD performance of the writing tool from the start to the end of the mask writing will never be measured. Thus, a typical CD measurement plan used today on a mask may indicate that the plate meets all CD specifications, but the resulting mask may still fail to meet the needs of the user. The typical user reaction to this problem – tighten the mask CD specification – does not address the real problem, and may even exacerbate it. Thus, the mask maker spends more time, energy and money making a mask that still does not meet the needs of the user.

I would like to propose a new approach to mask CD specifications: separately place CD specifications on the mask *and on the mask making process*. Densely populated electrical CD measurement test plates can be used to properly characterize the CD uniformity of the mask making process and base-line the behavior of mean-to-target CD through trend charts. These measurements can lead to specifications of CD uniformity and mean-to-target CD errors *for the process*. A separate measurement of CDs on a product mask can be used to characterize mean-to-target CD errors on a mask by mask basis.

The design of the electrical mask CD measurement test plates should be constrained by making the measurement structures as close to actual device structures as possible. For example, the "gate" test plate should contain a variety of horizontal and vertical lines of various feature sizes, pitches and duties, and should have local and global chrome/glass densities that are consistent with product reticles. A separate "contact" test reticle will be required. Measurements made with these test masks can be used to characterize both random and systematic errors in CD uniformity (such as proximity effects, linearity, and spatial CD variations).

Fundamentally, the problem with CD specifications and their associated measurements is the disconnect between what is being measured and what is important to the user. The old total quality adage applies quite well: you can only improve what you measure. This proposed change in strategy will, it is hoped, lead to an improvement in mask quality by adding rationality to the processes of mask CD specifications.

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