Golden Curve Method for OPC Signature Stability Control in high MEEF Applications

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ABSTRACT

The super-sensitivity of wafer critical dimensions (CDs) to mask CDs at low k_1, known as the Mask Error Enhancement Factor (MEEF) drives the need for increasingly tighter mask CD control. In addition, the accuracy of the model based optical proximity correction (OPC) used to compensate systematic lithographic errors is partially dependent on a stable mask CD error signature that expands mask CD control requirements over multiple feature types.

This paper presents the need for improved quantification and monitoring of mask CD signatures that includes CD characteristics relevant to OPC model calibration. It also introduces and discusses a new method to characterize, quantify, and control mask signatures in a mask manufacturing environment to limit the impact of mask CD variations on the OPC model validity. Multiple approaches to implementing this “golden curve” method are discussed in terms of their advantages and disadvantages.

Keywords: OPC, Optical Proximity Correction, Mask Error Enhancement Factor, MEEF, CD control, mask CD signature

1. INTRODUCTION

At k_1 factors ~0.5 and below, the optical lithography processes employed to produce integrated circuit devices no longer image all features with a 1:1 correspondence to the design input. This is due to bandwidth limitations of the optical system as well as resist and etch process effects such as diffusion[1] and loading[2] (different develop or etch rate as a function of pattern density or size). Optical Proximity Correction (OPC) methods are used to compensate for these effects and restore imaged features to their intended sizes.[3] OPC is typically accomplished by 1) breaking each figure into a series of edge fragments; 2) simulating the position of each edge fragment; and 3) moving the edge fragment such that the simulated position error is minimized. This is performed iteratively with software on the post-DRC design data in a step prior to mask tape-out. A model of the lithography process is used to perform the edge position simulation. The OPC model is generated both physically from known optical settings and empirically from line width measurements taken by scanning electron microscope (SEM) metrology systems from resist and etched images produced on the silicon wafer using the intended process. The OPC model typically represents one point in the exposure-defocus process window and is also representative of the process at the point in time when the line width measurements were taken. In practice, however, the OPC model must represent the average condition of the process and must generate acceptable results over the full intended process window. Deviations of the process beyond those the OPC model is designed to handle can cause undesirable imaging effects such as degraded line width or resist sidewall angle control or critical failures like bridging, pinching, and line-end shortening. The cost and time required to develop and verify an OPC model precludes altering the OPC model in response to changes in the imaging system (as part of automated process control, or APC, for example) and thus it is necessary to constrain and control the critical components of variability to assure good imaging performance over the desired process window and through time.

As part of the lithographic imaging system, the photomask is also represented in the OPC model, and its image characteristics and variability also have to be taken into account when considering control of the overall imaging performance of the system. The photomask is also generated with lithographic processes similar to those used in wafer fabrication.[4] Most advanced photomasks are produced using variable shaped beam (VSB) electron beam exposure tools to transfer the pattern represented in electronic data formats to a resist latent image which can then be developed. The chromium-based absorber and/or molybdenum silicide phase shift layers are then etched using the resist pattern as an etch mask. Limitations in the e-beam imaging tools and the resist and etch systems can cause imperfect transfer of design data to final image on the photomask.[5] The electron beam has chromatic aberrations that cause "beam blur" or a softening of the edge of a projected image.[6] Electrons are scattered upon entering the resist which further softens the projected image edge (forward scattering) but also causes proximity effects, where the electrons from one image add to the exposure of an adjacent image (back scattering).[7] Some backscattered electrons are reflected back to the final lens element of the electron beam optical column where they are in turn reflected back to the resist and finally absorbed (the fogging effect).[8] The resist materials used in photomask manufacturing exhibit diffusion and develop loading effects that result in localized pattern density dependent pattern size errors, and the plasma etch processes used to etch the absorber and phase shift films have loading effects based on local depletion of etch gasses. To some extent these pattern replication errors can be controlled and minimized. The electron back scatter effect is compensated by proximity effect correction (PEC) software in real time on the electron beam exposure tool. A similar method is used to compensate for the fogging effect (fogging effect correction, or FEC).[9] Other error sources have no specific compensation methods other than process tuning to achieve the best combination of results. Usually competing requirements results in a compromise where residual errors still exist.

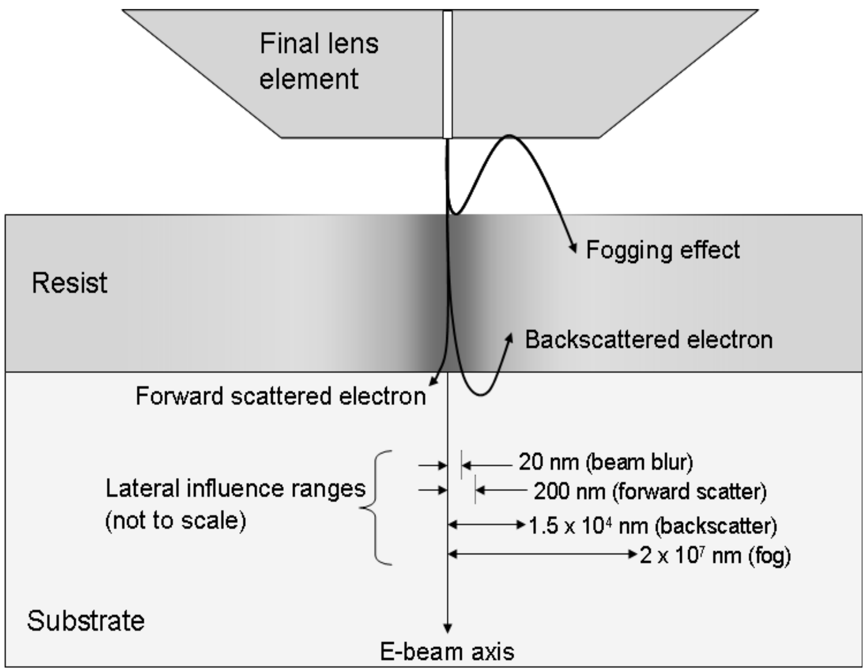

Figure 1: Electron beam – material interactions

To assure that the overall wafer lithography process remains represented by the OPC model, the mask error signature must be monitored and controlled. It is impractical to monitor each individual error source because of the complex interactions between them, so instead this is done by identifying key pattern error trends, or CD characteristics, that are important to the OPC model and tracking these. On wafer, the most critical CD characteristics include through-pitch bias (TPB) – the variation of line width as a function of line spacing; CD linearity – the variation of line width compared to it's target size as a function of target size; and line-end shortening (LES) – the line length error as a function of target line width, line spacing, and line-end spacing. TPB affects the CD of gate and metal lines as pattern density varies, particularly for random logic or the periphery of memory patterns. Mask linearity affects the performance of subresolution assist features (SRAFs). LES affects contact and via enclosure on metal layers. The stability of mask CD characteristics that related to wafer CD characteristics needs to be monitored to assure consistent OPC performance.

Choosing appropriate mask CD characteristics to monitor requires some consideration of the practical aspects of mask manufacturing. Producing photomasks differs from true manufacturing processes in several significant ways. While the processes and methods used to produce photomasks are standardized and controlled within a product line, each photomask is different from every other photomask because the pattern for each photomask is unique, with potentially a different size, area, and local pattern configuration. The contribution of the various error sources adds up uniquely on each mask. Because many of these affects are of a fairly long influence range[10] the placement of standardized test patterns is difficult. The center of the mask is reserved for the integrated circuit pattern, so it is often difficult to place test patterns there. The periphery of the circuit pattern is more assessable to the mask manufacturer but is potentially less representative of the total error contribution the circuit pattern sees. This can cause a mis-match between the characteristic as observed with a test pattern and that derived from in-die measurements. In-die measurements are not always possible depending on whether or not appropriate patterns to measure all of the monitored CD characteristics are present in the integrated circuit pattern. The cycle time of an advanced mask through lithography is long compared to wafer lithography, averaging 8-12 hours per mask and sometimes as long as 24 hours or more, while typical wafer throughput is 30-120 wafers/hour. Process perturbations or shifts on the order of or shorter than the mask cycle time are difficult to detect. This is exacerbated by low product volume in processes that are either at the end or beginning of their life cycles where the effective cycle time can be days or weeks between samples. The number of metrology sites on each mask also influences the value of the data. Of course, more sites measured are expected to produce a clearer picture of the CD characteristic in question, but the cost of metrology in terms of cycle time and fab capacity needs to be weighed against the value of the results.

The balance of this paper will describe an approach for monitoring important CD characteristics of photomask manufacturing and compare analysis methods to make meaningful inferences from the results.

2. EXPERIMENTAL

A parametric CD test pattern ("QA cell") has been developed that includes sub-patterns specifically designed to identify the signatures of many mask CD characteristics, but the primary focus of this paper will be on CD linearity. The QA cell is placed in four locations outside but close to the scribe boundary of the integrated circuit pattern, which we shall call the "primary" pattern. The QA cell in two of the locations is exposed with the same process bias as the primary pattern, which can vary from mask to mask depending on process loading effects. The other two QA cell locations are exposed with no bias regardless of how the primary pattern is exposed. CD measurements representing the linearity characteristic are taken from these QA cells on each mask produced. These CD measurements are normalized and compared to a set of "Golden Curves" that represent the average performance of the process and the mask CD signature encapsulated in the OPC model. The Golden Curves are generated from the average of a number of masks once the process has reached a stable state and a desired absolute signature. Deviations from the Golden Curves for data collected from each mask can be used to infer process health and to make process changes to retain the desired CD signature.

Reducing and normalizing the data such that meaningful inferences can be made from it can be challenging. One problem is that often there are unintended artifacts of other CD characteristics included – for instance, proximity effects can inadvertently be influencing CD linearity. This is to some extent a problem of test pattern design with limited area available to allocate for test pattern use. Another problem is the inclusion of metrology artifacts in the data – for instance, measuring the full CD linearity range of interest might require changing SEM magnification partway through and incurring a SEM calibration error for part of the data set. This can result in discontinuities where one expects a continuously smooth relationship between points.

Three reduction and normalization methods are considered. To illustrated these methods the QA cell data for clear dense CD linearity from eleven representative masks is used to create a representative Golden Curve. These masks were produced using a positive chemically amplified resist process (pCAR).

In the first approach, no assumptions are made about the relationship between data points. This avoids the need to interpret observed discontinuities in the data – these are just accepted as part of the signature being monitored. It is recognized that while the CD characteristic being monitored – CD linearity in this case – might be expected to be a continuous, smooth curve, we don't have the justification to impose that assumption on the data so we accept that we are monitoring some combination of CD linearity and other effects. If the total signature doesn't change, then we are confident that CD linearity hasn't either. Using this method, the Golden Curve is created by a point-by-point averaging of data from a number of representative masks and control limits are chosen, as illustrated in Figure 2. In use, each new mask data set is first normalized to the average of the larger feature sizes and then compared point-by-point to the Golden Curve (Figure 3). If any point deviates outside the control limits from its corresponding point on the Golden Curve the process is considered to be out of tolerance. This method has the disadvantage that it is very sensitive to metrology noise, especially for processes with low mask unit volume. It is difficult to make inferences from a single out of spec point. To address this, multiple measurements can be taken for each data point and averaged to reduce metrology noise. This makes it easier to detect real process changes with lower process volume but it requires additional metrology resources. With a fixed QA metrology budget, sometimes tradeoffs need to be made between the reduction of metrology noise and monitoring more points on the curve.

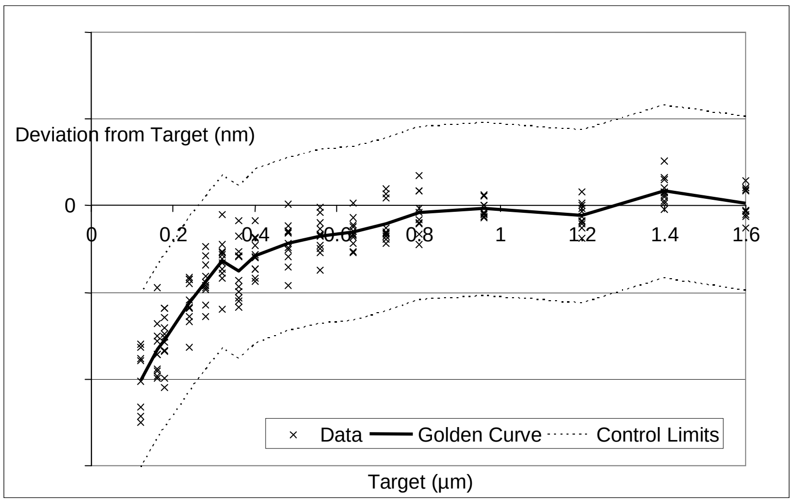

Figure 2: Golden Curve generated with point-by-point averaging

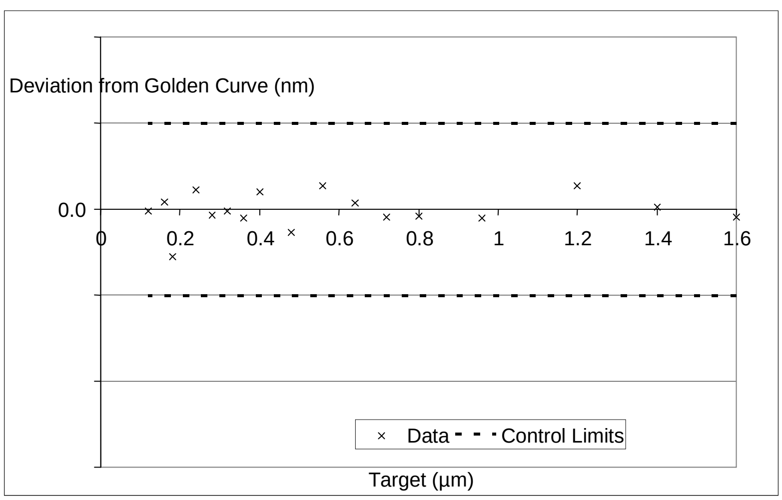

Figure 3: Comparing QA cell data from an individual mask to the Golden Curve.
The point-by-point deviation from the Golden Curve is compared to control limits.

A second method to reduce and normalize the data is to assume that the data predominantly represents the intended CD characteristic – in this case CD linearity – and that fitting the data to a function representing the general shape of the expected linearity curve will filter out influences not related to CD linearity. In this case we are making the assumption that most of the systematic variability is due to CD linearity and that the other influences are not large enough to substantially change our ability to extract the true CD linearity from the data. Using this method, the Golden Curve is created by merging the data from a number of representative masks and fitting this data set to a function (in this case the function is $y=a+b/x^{0.5}$) as shown in Figure 4. The shape of this curve becomes the Golden Curve. In use, each mask data set can also be fit to the same function and the deviation of this function compared to the Golden Curve. Figure 5 shows the fitted curves for each of the eleven data sets used to generate the Golden Curve. Alternatively, prediction limits can be established from the data used to create the Golden Curve, and each data set can be first normalized to the mean and then compared point-by-point to the prediction limits to defect out of tolerance conditions.

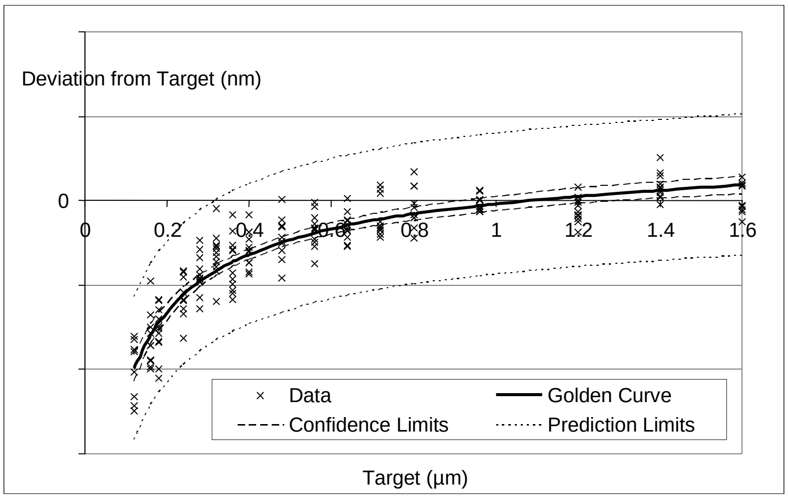

Figure 4: Golden Curve generated by fitting a function to representative data.

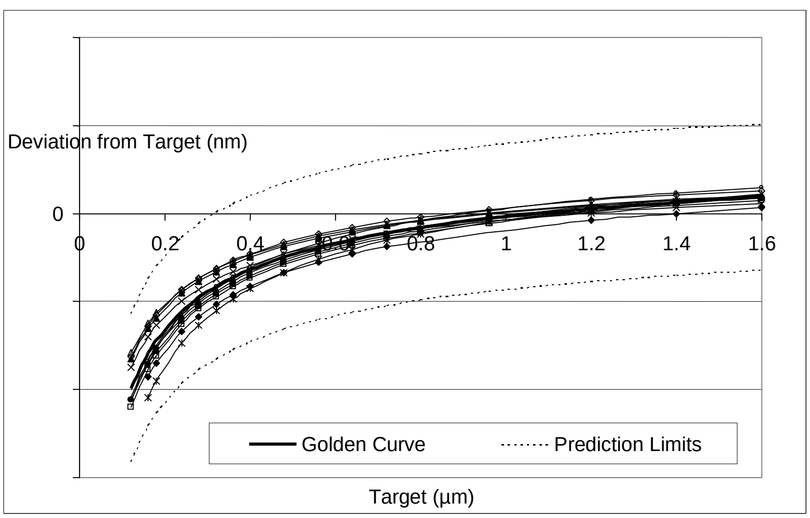

Figure 5: Comparing fitted curves for QA cell data from eleven masks to the Golden Curve.

The third approach, a variant of the fitting method, is to apply a smoothing function, such as a nearest-neighbor least squares fit, to the raw normalized off-target data. The same normalization method as used in the first approach is applied to this method. The smoothed data is compared to the Golden Curve. The Golden Curve can be generated in either of the two previously described methods.

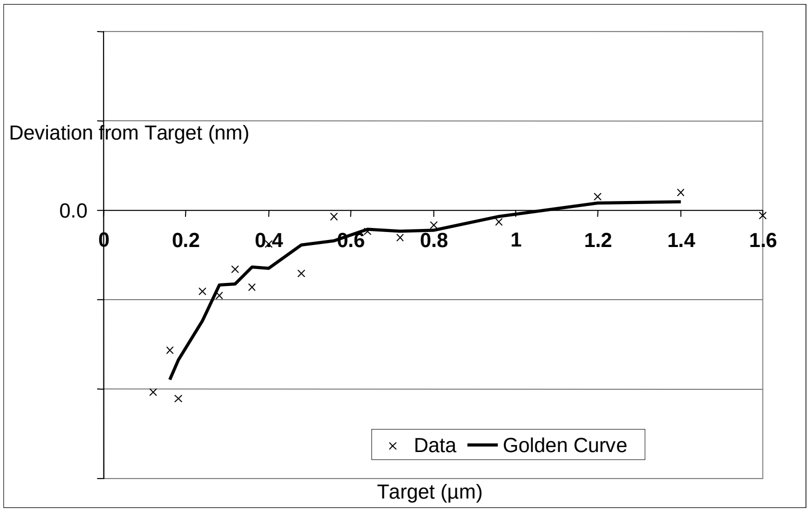

Figure 6: Data is fitted using the Least Square Method

All three fitting methods (including the least squares smoothing approach) have the advantage of filtering out metrology noise.

3. DISCUSSION

Control limits are generally chosen based on a pragmatic balance of mask manufacturing capability and OPC model requirements. However, the variability of the process sets real boundaries outside of which inferences about the data may no longer be valid. In the case of the point-by-point method the minimum valid control limits are likely to be ±3σ of the data sample point with the greatest variability, or ±5.4 nm for the example used in this paper. For the curve fitting method comparing whole individual mask data sets or fitted curves for each mask to the Golden Curve, the control limits should be set no tighter than the prediction limits for the Golden Curve, or ±4.3 nm for this example (see figure 4 again).

With the point-by-point method, stability of each point on the curve depends on samples taken at that point, so the ability to monitor the shape of the curve depends on regular sampling of every point of interest. With the curve fitting method, only sufficient data necessary to have confidence in the fit need be taken. More data ensures greater confidence in the fit. Figure 7 shows the confidence limits of the fit of a single mask data set compared with the Golden Curve and both it's confidence limits and prediction limits. While the single mask data set is part of the composite data set used to generate the Golden Curve, fewer data points significantly impacts the confidence limits of the fit.

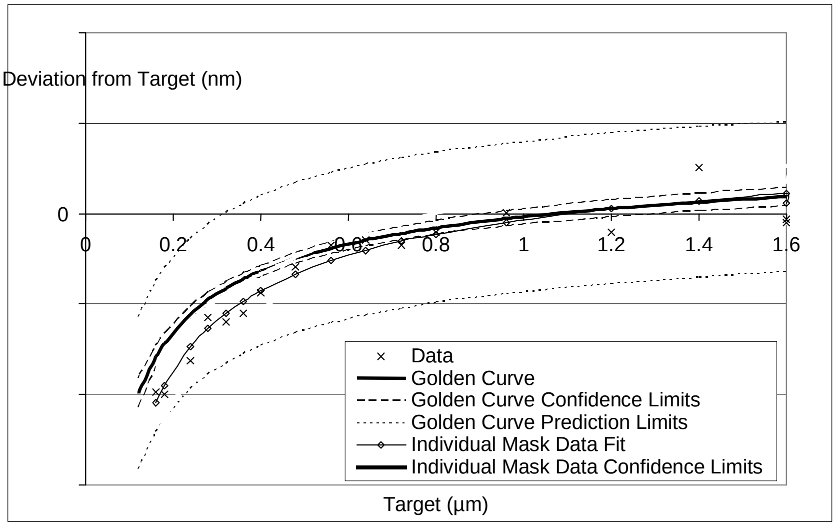

Figure 7: Comparing the confidence limits of the fit of an individual mask data set to that of the Golden Curve, created with significantly more data.

While the desire is to control a process to be invariant, in some cases it is necessary for the process to change. Mask processes and wafer processes for a given technology node are developed in parallel. The wafer process developers want their OPC model in place as soon as possible to verify that their process is manufacturable. At the time when the OPC model is being developed, the mask process is still not mature. This poses the possibility that either the mask process has to be "locked" before it is fully optimized or the OPC model will have to be re-verified and possibly changed once the final mask process is reached. Developing and monitoring Golden Curves early in the mask process development phase helps to determine the impact of mask process improvements on CD characteristics that impact the OPC model. If significant changes in critical CD characteristics occur, either the mask process has to retreat to the previous condition or the change must be made coordinated with revised OPC models. Successfully managing this coordinated development of wafer process, OPC models and mask process helps reach an optimized integrated process as quickly as possible.

When mask processes reach the end of their lifecycle, often there is not enough volume to justify the cost of maintaining the process. In addition, as mentioned previously, the total volume going through the process reaches some minimum level where process control is not longer possible. At this point it is desirable to migrate remaining product to newer processes. Typically newer processes have flatter CD characteristic signatures and also lower overall variability. While the change in CD characteristic signature can compromise the performance of the OPC model, the improvement in variability can often offset the difference in CD characteristic signature. Golden Curve methodology provides and objective means to assess these tradeoffs. Finally, the use of mask process compensation (MPC) methodology could potentially be used to synthesis the signature of the older process using the newer process.

4. CONCLUSIONS

Identifying and controlling mask CD characteristics that are important to the performance of OPC models are critical to the successful integration of masks into the wafer lithographic "system". Multiple systematic mask error sources combine to form complex error signatures that are somewhat pattern dependent. The uniqueness of each photomask makes monitoring these error sources difficult "in situ" with on-product metrology. Golden Curve methodology can help identify and track mask CD characteristics that are critical to the OPC model. Several methods to identify the Golden Curves for each process have been presented with advantages and disadvantages of both discussed. Golden Curve methodology has been shown to be useful to help dynamically develop mask processes in parallel with OPC models and wafer processes.

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