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This paper will propose standard methodologies for analyzing common lithographic data in three areas: photoresist contrast curves, swing curves, and focus-exposure matrices. For each data type, physics-based algebraic equations will be proposed to fit to the data. The equations will be fit to the data using standard non-linear least-squares fitting algorithms with standard statistical tests for removing data flyers and options for weighting the data. Analysis of the resulting curve fits will provide important information about the data.

1. INTRODUCTION

Although there has been previous work in the area of tools and techniques for lithographic data analysis [1-3], there exists today no standards, or even commonly accepted practices, for the analysis of lithographic data such as swing curves and critical dimension (CD) focus-exposure matrices. Most lithography engineers perform either no analysis or rudimentary spreadsheet analysis of focus-exposure matrix data to determine best focus and exposure, and very few fabs analyze this data to determine process windows or to calculate depth of focus in a rigorous way. Even simple analysis chores, such as finding the maximum of a swing curve, is typically done by "eye-balling" a graph of the data rather than using statistical techniques for assessing the data.

This paper will propose standard methodologies for analyzing common lithographic data in three areas: positive and negative resist contrast curves, reflectivity, E_o or CD swing curves, and focus-exposure matrices (using CD, sidewall angle, and/or resist loss data). For each data type, physics-based algebraic equations will be proposed to fit to the data. The coefficients of these equations will offer physical insight into the meaning and nature of the data. The equations will be fit to the data using standard non-linear least-squares fitting algorithms with standard statistical tests for removing data flyers and options for weighting the data. Analysis of the resulting curve fits will provide important information about the data. For the case of contrast curve data, the curve fits will yield resist contrast and dose-to-clear. For swing curves, the swing ratio, period and the positions of the minimums and maximums will be provided. For focus-exposure data, process windows will be generated based on resist profile specifications. These process windows will then be analyzed by fitting rectangles or ellipses inside the window and determining the resulting exposure latitude/depth of focus trade-off. Multiple process window overlaps can also be analyzed.

2. PHOTORESIST CONTRAST CURVES

The use of "contrast" to describe the response of a photosensitive material dates back over one hundred years. Hurter and Driffield measured the optical density of photographic negative plates as a function of log-exposure [4]. Photolithography evolved from photographic science and borrowed many of its concepts and terminology. When exposing a photographic plate, the goal is to change the optical density of the material. In lithography, the goal is to remove resist. Thus, an analogous Hurter-Driffield (H-D) curve for lithography might plot resist thickness after development versus log-exposure [5,6].

In order to derive an expression that adequately describes a typical H-D curve, the basic approach of Ziger and Mack [7] was used. The result for a positive resist is an equation of resist thickness (T_r) as a function of exposure dose (E):

$$T_r = T_o - \Delta T_{max}\left(1 - e^{-E/E^*}\right)^n \qquad (1)$$

where T_o = resist thickness remaining for no exposure, ΔT_{max} = maximum possible resist loss (assuming a very thick resist), E^* is a resist sensitivity term, and n is a resist contrast-like term. The case of a negative resist is slightly simpler:

$$T_r = T_o - \Delta T_{max} e^{-nE/E^*} \qquad (2)$$

Since both n and E^* are resist-dependent parameters, they can be lumped together into a new sensitivity term for negative resists, E_n^*

$$T_r = T_o - \Delta T_{max} e^{-E/E_n^*} \qquad (3)$$

An example of the application of equation (1) is shown in Figure 1.

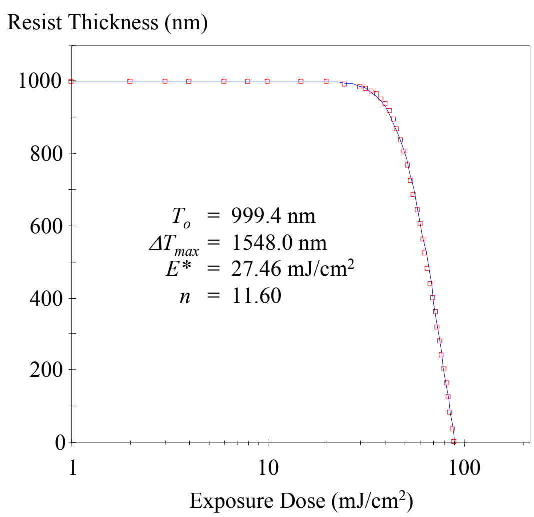

Figure 1. Example of a curve fit to contrast curve data for a positive resist.

From the curve fit equations, the contrast and the dose to clear can be extracted directly.

Positive Resist

$$E_o = -E^* \ln\left(1 - \left(\frac{T_o}{\Delta T_{max}}\right)^{1/n}\right)$$

$$\gamma = \frac{E_o}{E^*} n \left(\left(\frac{\Delta T_{max}}{T_o}\right)^{1/n} - 1\right)$$

Negative Resist

$$E_o = -E^* \ln\left(\frac{T_o}{\Delta T_{max}}\right)$$

$$\gamma = \frac{E_o}{E^*} \qquad (4)$$

3. SWING CURVES

Exposing a photoresist involves the propagation of light through a thin film of partially absorbing material (the resist) coated on a substrate which is somewhat reflective. The resulting thin film interference effects include standing waves [8] and swing curves [9]. Generically, a swing curve is the sinusoidal variation of some lithographic parameter with resist thickness.

The reflectivity swing curve shows that variations in resist thickness result in a sinusoidal variation in the reflectivity of the resist coated wafer. Since the definition of reflectivity is the total reflected light intensity divided by the total incident intensity, an increase in reflectivity results in more light which does not make it into the resist. Less light being coupled into the resist means that a higher dose is required to affect a certain chemical change in the resist, resulting in a larger E_o. Thus, the E_o and CD swing curves can both be explained by the reflectivity swing curve.

Analysis of the reflectivity swing curve leads to a simple approximate expression for reflectivity as a function of resist thickness (D):

$$R \approx aD + b + (cD + d)\cos(2\pi D/P + \phi) \qquad (5)$$

where $P = \lambda/2n_2$ = the swing curve period.

An approximate behavior of the E_o swing curve can be obtained from the reflectivity results above. Since the fraction of the light actually transmitted into the photoresist film is simply $1-R$, the energy deposited into the photoresist (E_{dep}) can be related to the incident dose (E_{inc}) by

$$E_{dep} = E_{inc}(1 - R) \qquad (6)$$

The incident dose will equal E_o when the deposited energy reaches some critical dose, E_{crit}.

$$E_o = \frac{E_{crit}}{(1 - R)} \qquad (7)$$

Algebraic manipulations and approximations similar to those used for the reflectivity swing curve will lead to an identical E_o swing curve form

$$E_o \approx aD + b + (cD + d)\cos(2\pi D / P + \phi) \qquad (8)$$

where the numerical values of a, b, c, and d will differ from those defined in equation (5).

Likewise, the CD swing curve can be directly related to the reflectivity swing curve. If one approximates the CD versus deposited exposure dose curve to be linear over a small region near the nominal dose, equation (6) in combination with the reflectivity swing curve will yield

$$CD \approx aD + b + (cD + d)\cos(2\pi D / P + \phi) \qquad (9)$$

where again the numerical values of a, b, c, and d will differ from previous values.

Figure 2 shows an example of fitting equation (8) to typical E_o swing curve data taken for an i-line resist on bare silicon.

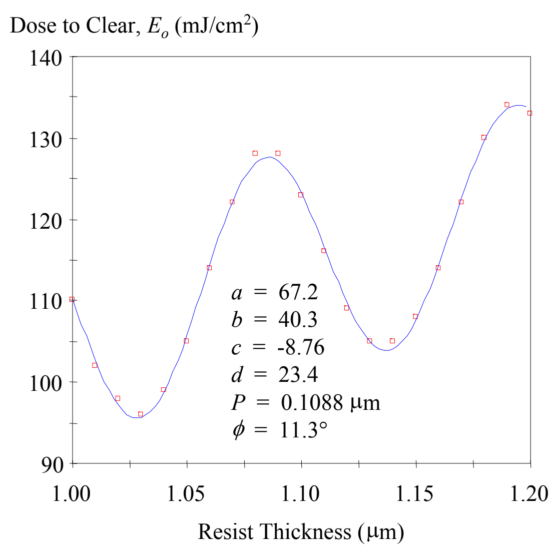

Figure 2. Best fit of equation (8) to E_o swing curve data.

4. FOCUS EXPOSURE MATRIX

The effects of focus and exposure on the results of a projection lithography system (such as a stepper) is a critical part of understanding and controlling a lithographic process.

In general, DOF can be thought of as the range of focus errors that a process can tolerate and still give acceptable lithographic results. Of course, the key to a good definition of DOF is in defining what is meant by tolerable. A change in focus results in two major changes to the final lithographic result: the photoresist profile changes and the sensitivity of the process to other processing errors is increased. Typically, photoresist profiles are described using three parameters: the linewidth (or critical dimension, CD), the sidewall angle, and the final resist thickness. The variation of these parameters with focus can be readily determined for any given set of conditions. The second effect of defocus is significantly harder to quantify: as an image goes out of focus, the process becomes more sensitive to other processing errors such as exposure dose and develop time. Of these secondary process errors, the most important is exposure.

Since the effect of focus is dependent on exposure, the only way to judge the response of the process to focus is to simultaneously vary both focus and exposure in what is known as a *focus-exposure matrix*. The resulting shapes of the Bossung curves (CD vs. focus for different exposures) are quite complicated. As a result, most efforts to fit this data to an equation has involved the use of polynomials in focus (F) and exposure (E) [1-3]. One very general expression is

$$CD = \sum_{i=0}^{3}\sum_{j=0}^{4} a_{ij} E^i F^j \qquad (10)$$

Although this function has 20 adjustable coefficients, for most data sets good fits are obtained when a_{03}, a_{22}, a_{14}, a_{23}, a_{24}, a_{33}, and a_{34} are fixed and set to zero.

Sidewall angle data as a function of focus and exposure can be measured from resist cross-sections. Although difficult to obtain, this data provides important information about the quality of the lithographic results. The following equation has been derived to describe the behavior of sidewall angle (*SA*) as a function of focus and exposure.

$$SA = \tan^{-1}\left(\left(1-\frac{E_o}{E}\right)^{\gamma}\left(\frac{E^*}{E}\right)^{\delta}\left(1+\left(\frac{F-F_o}{F^*}\right)^2\right)^{-1}\right),$$

$$F_o = aE + b \qquad (11)$$

where E_o = dose to clear-like term,
E^* = exposure sensitivity term,
γ = resist contrast-like term,
δ = strength of SA reduction at high doses,
F^* = depth of focus-like term,
F_o = best focus-like term,
a = slope of exposure variation of best focus, and
b = constant term of exposure variation of best focus.

Like sidewall angle, the loss of resist thickness in the center of a line feature can be measured using SEM cross-sections and provides insight into another mechanism for profile failure through focus and exposure. For positive resists, the following equation shows resist loss (*RL*) as a function of focus and exposure.

$$RL = (RLS)(E)^n\left(1+\left(\frac{F-F_o}{F^*}\right)^2\right)^n + RL_{min} \qquad (12)$$

where RLS = resist loss sensitivity term,
n = resist contrast-like term,
F_o = best focus-like term,
F^* = depth of focus-like term , and
RL_{min} = minimum (unexposed) resist loss.

Though not shown here, process windows can be generated from the best fits of CD, sidewall angle, and/or resist loss by plotting contours of the CD or profile specifications. Analysis of the process window allows calculation of the exposure latitude/depth of focus trade-off. Overlapping process windows can be used for common corridor analysis, determination of the iso-dense print bias, etc.

5. CONCLUSIONS

Data analysis is an important part of the photolithography engineer's job. As linewidth control becomes more critical and process windows become smaller and smaller, accurate analysis of lithography process data becomes essential. Simple techniques, such as plotting swing curve data and estimating the position of a maximum visually, or simply plotting a Bossung curve to guess best focus, is no longer adequate in most manufacturing environments. Automated, statistically sound techniques for analyzing data, removing bad data points, and extracting relevant lithographic information can dramatically improve one's ability to monitor, characterize, and optimize a process.

The techniques presented here have been incorporated into the software tool ProDATA™. This comprehensive lithographic data analysis tool employs the open curve-fit models described above and can form the basis of a standard methodology for many common semiconductor research, development, and manufacturing tasks.

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