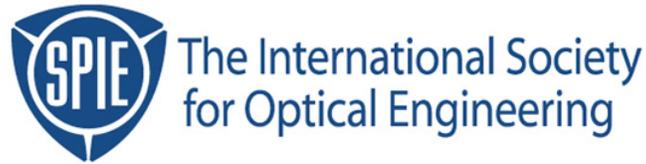


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# Resist Metrology for Lithography Simulation, Part 1: Exposure Parameter Measurements

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## *Abstract*

The experimental measurement of the photoresist ABC modeling parameters is described and three different data analysis techniques are compared. The best technique, the use of full exposure simulation to fit the data, is shown to be more accurate than the conventional data analysis method over a wide variety of typical substrates. In particular, artificial swing curve like behavior is observed on non-ideal substrates using the standard data analysis, but is readily accounted for in the more accurate full simulation method.

## **I. Introduction**

Since the introduction of lithography simulation more than twenty years ago, measurement of the parameters needed to model resist behavior has continued to be difficult. There are two basic sets of parameters needed when modeling a photoresist: exposure parameters and development parameters. The exposure parameters describe the optical properties of the resist (needed to calculate the actual light energy deposited in the resist) and the kinetic rate constant of the exposure reaction. Using the terminology of Dill [1], these parameters are the index of refraction of the resist (possibly as a function of exposure), and the ABC parameters (also called the Dill parameters).  $A$  is the bleachable absorption coefficient,  $B$  is the non-bleachable absorption coefficient, and  $C$  is the exposure rate constant. For resists which have a bleachable absorption coefficient different from zero, the ABC parameters can be measured with a single measurement of the transmission of the resist film at the exposure wavelength as a function of exposure dose.

This paper will describe the equipment and data analysis software needed to quickly and accurately measure the exposure parameters for lithography simulation. A specifically designed optical system exposes a resist film coated on a transparent substrate and measures the transmitted light intensity. By also monitoring the incident intensity, the result is a data table of transmittance versus exposure dose. Analysis of the data has a large impact on the accuracy of the resulting ABC values. Dill proposed two methods for analyzing the data [1]. The first, a graphical analysis, is very easy, but it does not make full use of the data set, cannot account for any non-idealities in the measurement, and requires the measurement of a slope, which amplifies any noise in the data. The second method solves the differential equations of exposure and absorption simultaneously to predict the transmittance curve and finds the ABC values which give a least squares error to the data. Since the entire data set is used, the result is a more accurate evaluation of the parameters. However, the

simple absorption equation assumes that the light traveling through the resist is traveling down only (i.e., the transparent substrate is optically matched to the photoresist and employs a backside antireflection coating). A third data analysis method is proposed in this paper which uses a lithography simulator to predict the transmittance of the actual resist/substrate configuration including standing waves due to a mismatched index of refraction of the substrate, and further exposure of the resist due to reflections from the backside of the wafer. In addition, changes in the index of refraction of the resist as a function of exposure can also be included. The result is a data analysis method which produces accurate results even in the case of the non-ideal experimental conditions. Extensive experimental results are shown to evaluate the overall accuracy and precision of the equipment and data analysis to produce ABC parameters.

## II. Theory

The kinetics of photoresist exposure is intimately tied to the phenomenon of absorption. The discussion below begins with a description of absorption, followed by the chemical kinetics of exposure. In describing the theory of exposure and absorption, the Dill ABC papers will be defined.

### A. Absorption

The phenomenon of absorption can be viewed on a macroscopic or a microscopic scale. On the macro level, absorption is described by the familiar Lambert and Beer laws which gives a linear relationship between absorbance and path length times the concentration of the absorbing species. On the micro level, a photon is absorbed by an atom or molecule, promoting an electron to a higher energy state. Both methods of analysis yield useful information needed in describing the effects of light on a photoresist.

The basic law of absorption is an empirical one with no known exceptions. It was first expressed by Lambert in differential form as

$$\frac{dI}{dz} = -\alpha I \quad (1)$$

where  $I$  is the intensity of light traveling in the  $z$ -direction through a medium, and  $\alpha$  is the absorption coefficient of the medium and has units of inverse length. In a homogeneous medium (i.e.,  $\alpha$  is not a function of  $z$ ), equation (1) may be integrated to yield

$$I(z) = I_0 \exp(-\alpha z) \quad (2)$$

where  $z$  is the distance the light has traveled through the medium and  $I_0$  is the intensity at  $z = 0$ . If the medium is inhomogeneous, equation (2) becomes

$$I(z) = I_0 \exp(-Abs(z)) \quad (3)$$

where

$$Abs(z) = \int_0^z \alpha(z') dz' = \text{the absorbance}$$

When working with electromagnetic radiation, it is often convenient to describe the radiation by its complex electric field vector. The electric field can implicitly account for absorption by using a complex index of refraction  $\mathbf{n}$  such that

$$\mathbf{n} = n - i\kappa \quad (4)$$

The imaginary part of the index of refraction, sometimes called the extinction coefficient, is related to the absorption coefficient by

$$\alpha = 4\pi\kappa/\lambda \quad (5)$$

In 1852 Beer showed that for dilute solutions the absorption coefficient is proportional to the concentration of the absorbing species in the solution.

$$\alpha_{solution} = ac \quad (6)$$

where  $a$  is the molar absorption coefficient, given by  $a = \alpha MW/\rho$ ,  $MW$  is the molecular weight,  $\rho$  is the density, and  $c$  is the concentration. The stipulation that the solution be dilute expresses a fundamental limitation of Beer's Law. At high concentrations, where absorbing molecules are close together, the absorption of a photon by one molecule may be affected by a nearby molecule [2]. Since this interaction is concentration dependent, it causes deviation from the linear relation (6). Also, an apparent deviation from Beer's law occurs if the real part of the index of refraction changes appreciably with concentration. Thus, the validity of Beer's Law should always be verified over the concentration range of interest.

For an  $N$  component homogeneous solid, the overall absorption coefficient becomes

$$\alpha_T = \sum_{j=1}^N a_j c_j \quad (7)$$

Of the total amount of light absorbed, the fraction of light which is absorbed by component  $i$  is given by

$$\frac{I_{Ai}}{I_{AT}} = \left( \frac{a_i c_i}{\alpha_T} \right) \quad (8)$$

where  $I_{AT}$  is the total light absorbed by the film, and  $I_{Ai}$  is the light absorbed by component  $i$ .

We will now apply the concepts of macroscopic absorption to a typical positive photoresist. A diazonaphthoquinone positive photoresist (such as AZ1350J) is made up of four major components; a

base resin  $R$  which gives the resist its structural properties, a photoactive compound  $M$  (abbreviated PAC), exposure products  $P$  generated by the reaction of  $M$  with ultraviolet light, and a solvent  $S$ . Although photoresist drying during prebake is intended to drive off solvents, thermal studies have shown that a resist may contain 10% solvent after a 30 minute, 100°C prebake [3,4]. The absorption coefficient  $\alpha$  is then

$$\alpha = a_M M + a_P P + a_R R + a_S S \quad (9)$$

If  $M_0$  is the initial PAC concentration (i.e., with no UV exposure), the stoichiometry of the exposure reaction gives

$$P = M_0 - M \quad (10)$$

Equation (9) may be re-written as [1]

$$\alpha = A m + B \quad (11)$$

where  $A = (a_M - a_P)M_0$

$$B = a_P M_0 + a_R R + a_S S$$

$$m = M/M_0$$

$A$  and  $B$  are called the bleachable and non-bleachable absorption coefficients, respectively, and make up the first two Dill photoresist parameters [1].

The quantities  $A$  and  $B$  are experimentally measurable [1] and can be easily related to typical resist absorbance curves, measured using an UV spectrophotometer. When the resist is fully exposed,  $M=0$  and

$$\alpha_{exposed} = B \quad (12)$$

Similarly, when the resist is unexposed,  $m = 1$  ( $M = M_0$ ) and

$$\alpha_{unexposed} = A + B \quad (13)$$

From this  $A$  may be found by

$$A = \alpha_{unexposed} - \alpha_{exposed} \quad (14)$$

Thus,  $A(\lambda)$  and  $B(\lambda)$  may be approximated from the UV absorbance curves of unexposed and completely exposed resist (Figure 1). More careful measurement of these parameters will be described in the following section.

As mentioned previously, Beer's law is empirical in nature and, thus, should be verified experimentally. In the case of positive photoresists, this means formulating resist mixtures with

differing photoactive compound to resin ratios and measuring the resulting  $A$  parameters. Previous work has shown that Beer's Law is valid for conventional photoresists over the full practical range of PAC concentrations [5].

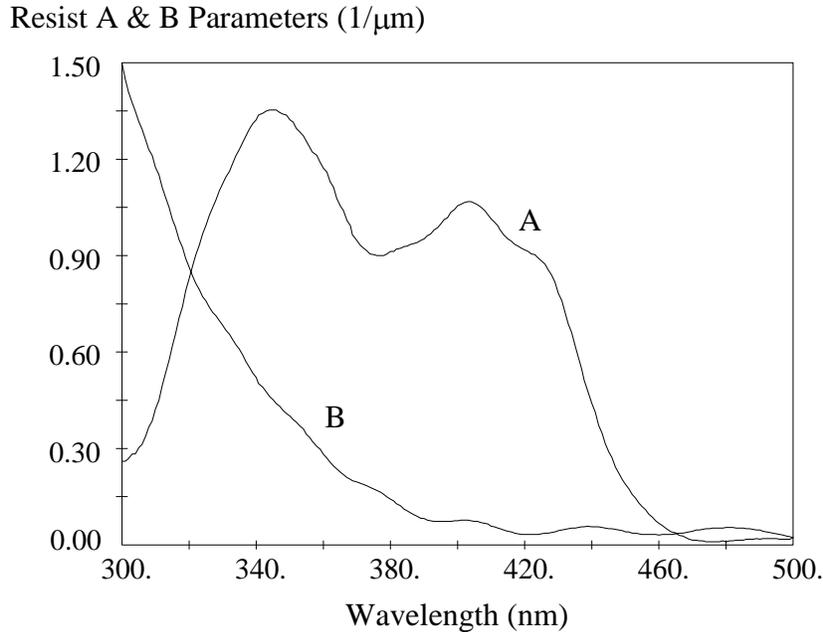


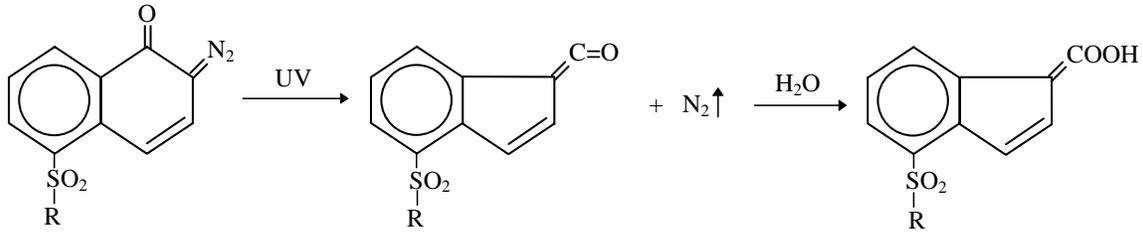
Figure 1. Resist parameters A and B as a function of wavelength measured (approximately) using a UV spectrophotometer.

## B. Exposure Kinetics

On a microscopic level, the absorption process can be thought of as photons being absorbed by an atom or molecule causing an outer electron to be promoted to a higher energy state. This phenomenon is especially important for the photoactive compound since it is the absorption of UV light which leads to the chemical conversion of  $M$  to  $P$ .



This concept is stated in the first law of photochemistry: only the light which is absorbed by a molecule can be effective in producing photochemical change in the molecule. The actual chemistry of diazonaphthoquinone exposure is given below.



The chemical reaction (15) can be rewritten in general form as



where  $M$  = the photoactive compound (PAC);  $M^*$  = molecule in an excited state;  $P$  = the carboxylic acid (product); and  $k_1$ ,  $k_2$ ,  $k_3$  = the rate constants for each reaction. Simple kinetics can now be applied. The proposed mechanism (16) assumes that all reactions are first order. Thus, the rate equation for each species can be written.

$$\begin{aligned} \frac{dM}{dt} &= k_2 M^* - k_1 M \\ \frac{dM^*}{dt} &= k_1 M - (k_2 + k_3) M^* \\ \frac{dP}{dt} &= k_3 M^* \end{aligned} \quad (17)$$

A system of three coupled linear first order differential equations can be solved exactly using Laplace transforms and the initial conditions

$$\begin{aligned} M(t=0) &= M_0 \\ M^*(t=0) &= P(t=0) = 0 \end{aligned} \quad (18)$$

However, if one uses the steady state approximation the solution becomes much simpler. This approximation assumes that in a very short time the excited molecule  $M^*$  comes to a steady state, i.e.,  $M^*$  is formed as quickly as it disappears. In mathematical form,

$$\frac{dM^*}{dt} = 0 \quad (19)$$

A previous study has shown that  $M^*$  does indeed come to a steady state quickly, on the order of  $10^{-8}$  seconds or faster [6]. Thus,

$$\frac{dM}{dt} = -KM \quad (20)$$

where

$$K = \frac{k_1 k_3}{k_2 + k_3}$$

Assuming  $K$  remains constant with time,

$$M = M_o \exp(-Kt) \quad (21)$$

The overall rate constant  $K$  is a function of the intensity of the exposure radiation. An analysis of the microscopic absorption of a photon predicts that  $k_1$  (and thus  $K$ ) is directly proportional to the intensity of the exposing radiation [5]. Thus, a more useful form of equation (20) is

$$\frac{dm}{dt} = -CIm \quad (22)$$

where the relative PAC concentration  $m (= M/M_o)$  has been used and  $C$  is the standard exposure rate constant and the third Dill photoresist parameter.

A solution to the exposure rate equation (22) is simple if the intensity within the resist is constant throughout the exposure. However, this is generally not the case. In fact, many resists *bleach* upon exposure, that is, they become more transparent as the photoactive compound  $M$  is converted to product  $P$ . This corresponds to a positive value of  $A$ , as seen, for example, in Figure 1. Since the intensity varies as a function of exposure time, this variation must be known in order to solve the exposure rate equation. In the simplest possible case, a resist film coated on a substrate of the same index of refraction, only absorption affects the intensity within the resist. Thus, Lambert's Law of absorption, coupled with Beer's Law, could be applied.

$$\frac{dI}{dz} = -(Am + B)I \quad (23)$$

where equation (11) was used to relate the absorption coefficient to the relative PAC concentration. Equations (22) and (23) are coupled, and thus become first order non-linear partial differential equations which must be solved simultaneous. The solution to equations (22) and (23) was first carried out numerically for the case of lithography simulation [1], but in fact was solved analytically by Herrick [7] many years earlier. The same solution was also presented more recently by Diamond and Sheats [8] and by Babu and Barouch [9]. These solutions take the form of a single numerical integration, which is much simpler than solving two differential equations!

Although an analytical solution exists for the simple problem of exposure with absorption only, in more realistic problems the variation of intensity with depth in the film is more complicated than equation (23). In fact, the general exposure situation results in the formation of standing waves.

Obviously, such general conditions greatly complicate the resulting exposure of the photoresist. For that reason, experimental measurement of the ABC parameters involves trying to mimic the simple exposure situation described by equations (22) and (23) as closely as possible.

### III. Measurement of the ABC Parameters

Dill proposed a single, simple experiment for measuring the ABC parameters [1]. The photoresist to be measured is coated in a non-reflecting substrate (e.g., glass, quartz, or similar material). The resist is then exposed by a normally incident parallel beam of light at the wavelength of measurement. At the same time, the intensity of the light transmitted through the substrate is measured continuously. The output of the experiment, transmitted intensity as a function of exposure time, is then analyzed to determine the resist ABC parameters. A typical experimental setup is shown in Figure 2.

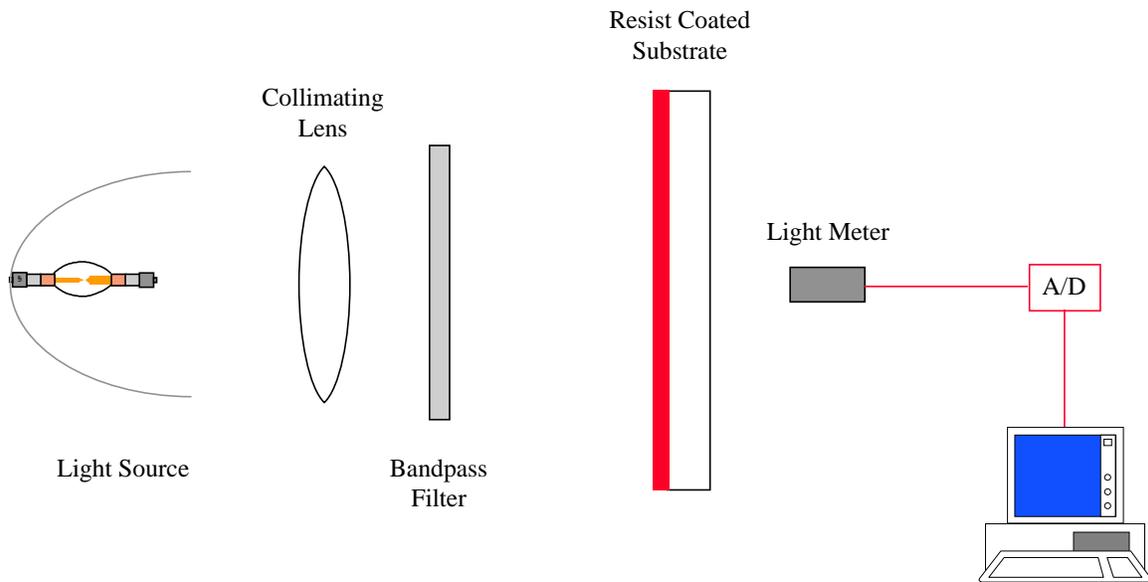


Figure 2. Experimental configuration for the measurement of the ABC parameters.

By measuring the incident exposing light intensity, the output of the experiment becomes overall transmittance as a function of incident exposure dose,  $T(E)$ . Figure 3 shows a typical result. Assuming careful measurement of this function, and a knowledge of the thickness of the photoresist, all that remains is the analysis of the data to extract the ABC parameters. Dill proposed two methods for extracting the parameters [1]. Those methods will be reviewed here and a third, more accurate approach will be introduced.

Note that the effectiveness of this measurement technique rests with the non-zero value of  $A$ . If the photoresist does not change its optical properties with exposure (i.e., if  $A = 0$ ), then measuring transmittance will provide no insight on the exposure reaction, making  $C$  unobtainable by this method.

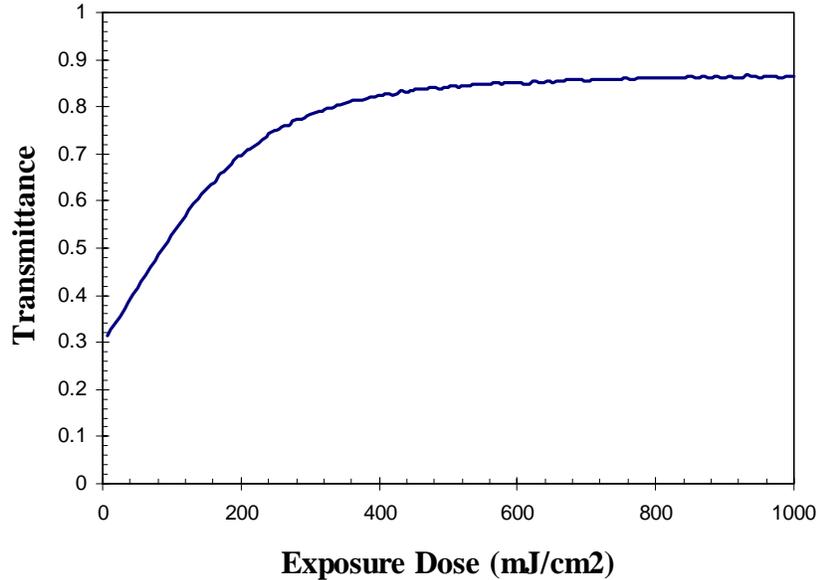


Figure 3. Typical transmittance curve of a positive  $g$ - or  $i$ -line bleaching photoresist measured using an apparatus similar to that pictured in Figure 3.

### A. Graphical Data Analysis (Method 1)

Analysis of the experimental data is greatly simplified if the experimental conditions are adjusted so that the simple exposure and absorption equations (22) and (23) apply exactly. This means that light passing through the resist must not reflect at the resist/substrate interface. Further, light passing through the substrate must not reflect at the substrate/air interface. The first requirement is met by producing a transparent substrate with the same index of refraction as the photoresist. The second requirement is met by coating the backside of the substrate with an interference-type antireflection coating (ARC).

Given such ideal measurement conditions, Dill showed that the ABC parameters can be obtained from the transmittance curve by measuring the initial transmittance  $T(0)$ , the final (completely exposed) transmittance  $T(\infty)$ , and the initial slope of the curve. The relationships are:

$$A = \frac{1}{D} \ln \left( \frac{T(\infty)}{T(0)} \right) \quad (24a)$$

$$B = -\frac{1}{D}\ln(T(\infty)) \quad (24b)$$

$$C = \frac{A+B}{AT(0)\{1-T(0)\}T_{12}} \left. \frac{dT}{dE} \right|_{E=0} \quad (24c)$$

where  $D$  is the resist thickness and  $T_{12}$  is the transmittance of the air-resist interface and is given, for a resist index of refraction  $n_{resist}$ , by

$$T_{12} = 1 - \left( \frac{n_{resist} - 1}{n_{resist} + 1} \right)^2 \quad (25)$$

## B. Differential Equation Solution (Method 2)

Although graphical analysis of the data is quite simple, it suffers from the common problem of errors when measuring the slope of experimental data. As a result, the value of  $C$  (and to a lesser extent,  $A$ ) obtained often contains significant error. Dill also proposed a second method for extracting the ABC parameters from the data. Again assuming that the ideal experimental conditions had been met, the ABC parameters could be obtained by directly solving the two coupled partial differential equations (22) and (23) and finding the values of  $A$ ,  $B$ , and  $C$  for which the solution best fits the experimental data. Obviously, fitting the entire experimental curve is much less sensitive to noise in the data than taking the slope at one point. Several techniques are available to provide a simple numerical solution [7-9].

## C. Full Simulation (Method 3)

Methods 1 and 2 give accurate results only to the extent that the actual experimental conditions match the ideal (no reflection) conditions. In reality, there will always be some deviation from this ideal. Substrates will invariably have an index somewhat different that of the photoresist. And since the index of refraction of the photoresist changes with exposure, even a perfect substrate will be optically matched at only one instant in time during the experiment. Backside ARCs may also be less than perfect. In fact, most experimenters would prefer to use off-the-shelf glass or quartz wafers with no backside ARC. Under these conditions, how accurate are the extracted ABC parameters?

The dilemma can be solved by eliminating the restrictions of the ideal experiment. Rather than solving for the transmitted intensity via equations (22) and (23), one could use a lithography simulator to solve for the transmittance in a non-ideal case including changes in the resist index of refraction during exposure and reflections from both the top and bottom of the substrate. Then, by adjusting the ABC parameters, a best fit of the model to the data could be obtained. This method provides the ultimate accuracy in obtaining extracted ABC parameters.

## IV. Experimental Conditions

In this work a commercial ABC measurement tool was used (the ABC-Analyzer made by Litho Tech Japan) [10]. This fully automated measurement tool uses a 150W Xe-Hg arc lamp and a user-selectable filter to pick the measurement wavelength. Standard filters include 436nm (4nm FWHM), 365nm (4nm FWHM), and 248nm (11nm FWHM) and result in intensities at the wafer of about 5-6 mW/cm<sup>2</sup>. The optical system produces a small collimated beam, roughly Gaussian in shape, with a beam width of about 8mm FWHM. The center 4mm of the beam is uniform to within  $\pm 3\%$ . A silicon photodiode is used to measure the transmitted light (and the same photodiode is used to measure the incident intensity before and after the substrate is inserted in the optical path). The output voltage of the diode was calibrated to intensity at each measurement wavelength using standard Ushio brand UV-meters with probes appropriate to the wavelength. The output voltage is sent to an A/D converter and then to a personal computer for collection. The A/D converter has a minimum sampling interval of 0.5 seconds, but a 1 second sampling rate is typically used. Up to 2000 measurement points can be stored for one transmittance curve (the curve shown in Figure 3 contains 160 measured points and rarely are more than 500 needed).

For the data collected in this work, only 365nm exposure light was used. Four different substrates were used to examine the effects of their optical properties on measurement accuracy. First, a standard quartz wafer ( $n = 1.474$ ) with no backside AR coating (labeled QZ1 here) was used. The second substrate added an antireflection coating ( $n = 1.214$ ,  $d = 752\text{\AA}$ ) to the back of the standard quartz wafer (labeled QZ1AR). The third substrate ( $n = 1.7305$ ) was made of a glass specially chosen to closely match the index of refraction of the photoresist, and did not use an AR coating (labeled GL1). Finally, the fourth substrate used a matched index ( $n = 1.7011$ ) and a backside ARC ( $n = 1.3040$ ,  $d = 700\text{\AA}$ ) and represents close to the ideal measurement conditions (labeled GL2AR).

The resist used for all tests was THMR-iP3000 from Tokyo Ohka Kogyo. This i-line photoresist was applied to the various substrates on a commercial coat/bake track to a thickness of nominally 1.0  $\mu\text{m}$  and hotplate baked at 80°C for 90 seconds. The mild bake was intended to limit the magnitude of photoresist PAC thermal decomposition [11]. The thickness of the photoresist is difficult to measure on a transparent substrate. To overcome this problem, a silicon wafer was coated immediately prior to the coating of the measurement sample under identical conditions. The thickness of the resist layer on silicon was then measured using a Nanospec AFT. It was assumed that the control of the coat/bake process was sufficient to ensure that the resist coated on the transparent substrate was the same thickness as that of the silicon wafer to within about 100 $\text{\AA}$ . Transmittance measurements were carried out in the LTJ ABC-Analyzer and the results were analyzed using all three of the above methods with the software package ProABC from FINLE Technologies.

## V. Results

Since the same resist and resist processing conditions were used for all experiments, one could assume that the true values of the ABC parameters did not vary significantly from test to test. Thus, one goal of a good data collection and analysis method would be to produce the same measured ABC

values over the range of substrates used. Table I shows a comparison of the measured ABC values for the four different substrates, each analyzed with the three methods described above.

Table I. Comparison of ABC analysis methods on four different substrates

Substrate	Analysis Method 1 (graphical)			Analysis Method 2 (equation solution)			Analysis Method 3 (full simulation)		
	A ( $\mu\text{m}^{-1}$ )	B ( $\mu\text{m}^{-1}$ )	C ( $\text{cm}^2/\text{mJ}$ )	A ( $\mu\text{m}^{-1}$ )	B ( $\mu\text{m}^{-1}$ )	C ( $\text{cm}^2/\text{mJ}$ )	A ( $\mu\text{m}^{-1}$ )	B ( $\mu\text{m}^{-1}$ )	C ( $\text{cm}^2/\text{mJ}$ )
QZ1	0.6667	0.1152	0.0083	0.6273	0.1152	0.0068	0.6521	0.0483	0.0076
QZ1AR	0.6677	0.0774	0.0083	0.6347	0.0774	0.0073	0.6565	0.0424	0.0081
GL1	0.6934	0.1166	0.0090	0.6524	0.1166	0.0073	0.6475	0.0582	0.0079
GL2AR	0.6862	0.0519	0.0076	0.6458	0.0519	0.0067	0.6497	0.0596	0.0076

Several important observations can be made from Table I. The  $B$  parameter is the most sensitive to variations in the substrate properties. For analysis methods 1 and 2, the measured value of  $B$  varies by  $0.065 \mu\text{m}^{-1}$  for the four substrates. However, the use of analysis method 3 reduces the variation of the measurement by over a factor of 3. Overall, analysis method 3 gives consistent values of  $A$ ,  $B$ , and  $C$  for all of the substrates. Notice also that for the nearly ideal substrate GL2AR, all three analysis methods give about the same result. As expected, when the substrate matches the assumptions of the analysis methods, good results are obtained. Only method 3 is capable of handling the non-ideal substrates accurately.

The problem of a non-ideal substrate is exacerbated by changes in the resist thickness. If there is a mismatch in the index of refraction of the resist and the substrate, changes in resist thickness will cause a swing curve-like behavior [10]. Different resist thicknesses result in different couplings of energy into the film and, as a result, different transmittances through the film. Absorption by the unexposed resist attenuates the effect significantly, but the fully exposed resist shows a significant variation. The QZ1 substrate was coated with several resist thicknesses and the ABC parameters measured. Figure 4 shows the final transmittance of fully exposed resist,  $T(\infty)$ , as a function of resist thickness. The obvious swing curve behavior will lead to the same cyclical variation in the value of  $B$  using analysis methods 1 or 2. However, method 3 accounts for the underlying physics of these thin film interference effects and gives a more correct value. It is interesting to note that this swing curve can be used to give an accurate estimate of the index of refraction of the exposed resist. Since there is essentially no phase change of the light upon reflection from the quartz substrate, a maximum of the swing curve will occur at thicknesses equal to integer multiples of the wavelength divided by two times the index of refraction of the resist (which is the period of the swing curve). This resist is known to have an index of refraction of about 1.7 so that the peak at about a thickness of  $1.05\mu\text{m}$  corresponds to ten periods. This peak will be exactly ten periods when the index of refraction of the resist is 1.735. This value of the exposed index of refraction is used for all of the analysis shown above and below. The unexposed resist index of refraction was not measured and was assumed to be 0.02 less than the exposed index.

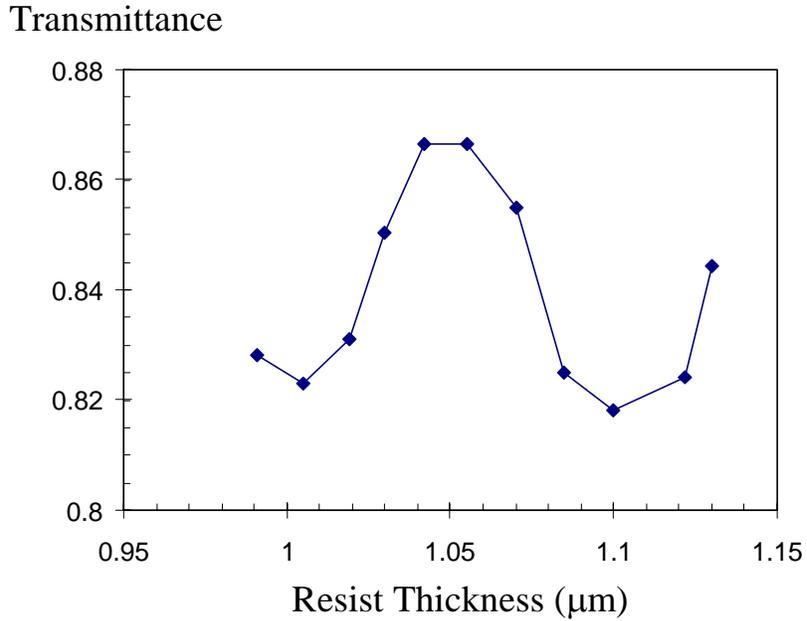


Figure 4. The final transmittance of fully exposed resist on the QZ1 substrate shows a significant swing curve effect.

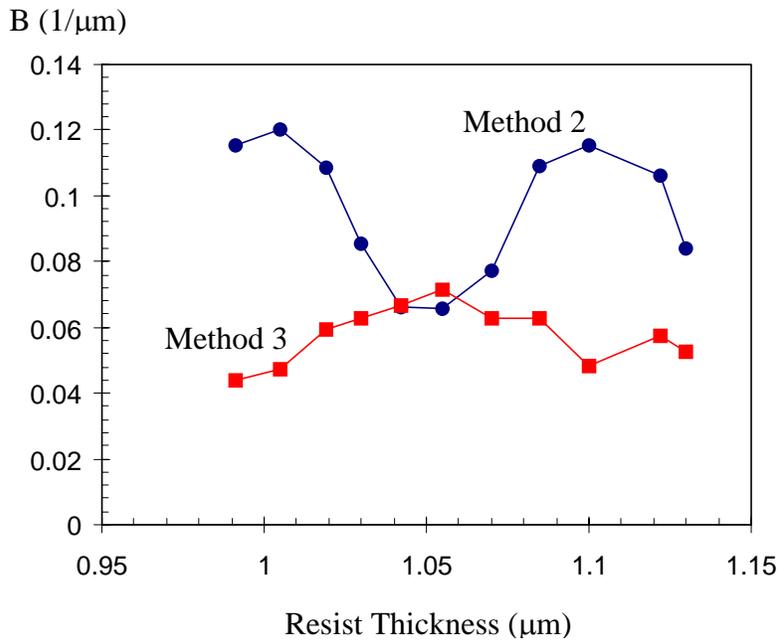


Figure 5. Comparison of analysis methods for calculating  $B$  with measurements made on a slightly reflecting substrate (QZ1).

The eleven quartz wafers with different resist thickness were analyzed to determine their ABC values. Figure 5 shows a plot of the  $B$  values resulting from analysis methods 2 and 3 as a function of resist thickness. Method 2 shows a large artificial “swing” due to the incorrect assumption of the analysis method. Method 3 gives a much more stable value of  $B$ , but still exhibits a slight swing, though out of phase with the original. This is an indication that the model used in method 3 is over-predicting the magnitude of the swing effect. The mismatch in the index of refraction between the quartz and the resist used in the model was probably slightly exaggerated.

As a final test, the other three substrates were also coated with a range of resist thicknesses and analyzed to determine the ABC values. As expected, the ideal substrate showed no swing-like effects and produced comparable values of  $A$ ,  $B$  and  $C$  for all analysis methods. The data below shows the average and standard deviations of the resulting ABC parameters for each substrate type.

	Method 2	Method 3
Substrate QZ1	A = $0.64 \pm 0.01 \mu\text{m}^{-1}$ B = $0.096 \pm 0.020 \mu\text{m}^{-1}$ C = $0.0071 \pm 0.0002 \text{ cm}^2/\text{mJ}$	A = $0.64 \pm 0.015 \mu\text{m}^{-1}$ B = $0.058 \pm 0.009 \mu\text{m}^{-1}$ C = $0.00770 \pm 0.0002 \text{ cm}^2/\text{mJ}$
Substrate QZ1AR	A = $0.65 \pm 0.01 \mu\text{m}^{-1}$ B = $0.051 \pm 0.016 \mu\text{m}^{-1}$ C = $0.0076 \pm 0.0003 \text{ cm}^2/\text{mJ}$	A = $0.65 \pm 0.015 \mu\text{m}^{-1}$ B = $0.052 \pm 0.013 \mu\text{m}^{-1}$ C = $0.0084 \pm 0.0004 \text{ cm}^2/\text{mJ}$
Substrate GL1	A = $0.645 \pm 0.006 \mu\text{m}^{-1}$ B = $0.051 \pm 0.011 \mu\text{m}^{-1}$ C = $0.0074 \pm 0.0001 \text{ cm}^2/\text{mJ}$	A = $0.641 \pm 0.008 \mu\text{m}^{-1}$ B = $0.060 \pm 0.007 \mu\text{m}^{-1}$ C = $0.0080 \pm 0.0001 \text{ cm}^2/\text{mJ}$
Substrate GL2AR	A = $0.651 \pm 0.009 \mu\text{m}^{-1}$ B = $0.053 \pm 0.002 \mu\text{m}^{-1}$ C = $0.0069 \pm 0.0002 \text{ cm}^2/\text{mJ}$	A = $0.649 \pm 0.009 \mu\text{m}^{-1}$ B = $0.063 \pm 0.004 \mu\text{m}^{-1}$ C = $0.0077 \pm 0.0001 \text{ cm}^2/\text{mJ}$
All Wafers Combined	A = $0.65 \pm 0.01 \mu\text{m}^{-1}$ B = $0.079 \pm 0.033 \mu\text{m}^{-1}$ C = $0.0073 \pm 0.0003 \text{ cm}^2/\text{mJ}$	A = $0.64 \pm 0.01 \mu\text{m}^{-1}$ B = $0.057 \pm 0.010 \mu\text{m}^{-1}$ C = $0.0080 \pm 0.0004 \text{ cm}^2/\text{mJ}$

The worse case substrate, as expected, was the quartz wafer (QZ1). For this case, use of the best analysis method (method 3) allowed  $A$  to be measured with 2% precision,  $B$  within 25%, and  $C$  with a precision of 5% over the full range of resist thicknesses. The relative precision of the measurement of  $B$  will improve greatly for larger  $B$ .

## VI. Conclusions

The measurement of the Dill ABC parameters is an important part of accurate lithography simulation. As simulation acquires more prominence in lithography process research, development, and manufacturing, the need for accurate parameters increases. In this paper we have examined a major limitation to accurate measurement of the Dill parameters -- non-ideal substrates and the related resist thickness dependency. It was discovered that this source of inaccuracy can be virtually eliminated either through the use of near ideal substrates or, more economically, through the use of sophisticated data analysis. The software package ProABC was developed to meet this need. This software, in combination with the ABC-Analyzer tool, was found to provide a convenient and accurate method for measuring the important ABC photoresist modeling parameters.

## References

1. F. H. Dill, W. P. Hornberger, P. S. Hauge, and J. M. Shaw, "Characterization of Positive Photoresist," *IEEE Transaction on Electron Devices*, ED-22, No. 4 (1975) pp. 445-452.
2. D. A. Skoog and D. M. West, Fundamentals of Analytical Chemistry, 3rd edition, Holt, Rinehart, and Winston (New York :1976), pp. 509-510.
3. J. M. Koyler, et al., "Thermal Properties of Positive Photoresist and their Relationship to VLSI Processing," *Kodak Microelectronics Seminar Interface '79*, (1979) pp. 150-165.
4. J. M. Shaw, M. A. Frisch, and F. H. Dill, "Thermal Analysis of Positive Photoresist Films by Mass Spectrometry," *IBM Jour. Res. Dev.*, Vol 21 (May, 1977), pp. 219-226.
5. C. A. Mack, "Absorption and Exposure in Positive Photoresist," *Applied Optics*, Vol. 27, No. 23 (1 Dec. 1988) pp. 4913-4919.
6. J. Albers and D. B. Novotny, "Intensity Dependence of Photochemical Reaction Rates for Photoresists," *Jour. Electrochem. Soc.*, Vol. 127, No. 6 (June, 1980) pp. 1400-1403.
7. C. E. Herrick, Jr., "Solution of the Partial Differential Equations Describing Photo-decomposition in a Light-absorbing Matrix having Light-absorbing Photoproducts," *IBM Journal of Research and Development*, Vol. 10 (Jan., 1966) pp. 2-5.
8. J. J. Diamond and J. R. Sheats, "Simple Algebraic Description of Photoresist Exposure and Contrast Enhancement," *IEEE Electron Device Letters*, Vol. EDL-7, No. 6 (June, 1986) pp. 383-386.
9. S. V. Babu and E. Barouch, "Exact Solution of Dill's Model Equations for Positive Photoresist Kinetics," *IEEE Electron Device Letters*, Vol. EDL-7, No. 4 (April, 1986) pp. 252-253.
10. A. Sekiguchi, Y. Minami, T. Matsuzawa, T. Takezawa, and H. Miyakawa, "Measuring System of A, B, and C Photoresist Parameters," *Electronics and Communications in Japan, Part 2*, Vol. 78, No. 5 (1995) pp. 21 - 30.

11. C. A. Mack and R. T. Carback, "Modeling the Effects of Prebake on Positive Resist Processing," *Kodak Microelectronics Seminar, Proc.*, (1985) pp. 155-158.