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Technique for the measurement of the in-situ development rate

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ABSTRACT

In the past, a Perkin Elmer Development Rate Monitor (DRM) has been used to measure the development rate of photoresist. However, due to several limitations of the DRM, the development rates measured therein, are not truly representative of the resist processing on a production line. Subtleties in the development system are not obtained through the DRM and hence an in-situ development rate is required.

Using a Site Services Development Spray Monitor (DSM 100) and a post processing algorithm, the in-situ measured development rates were obtained. The interference signals for eight different wavelengths were simultaneously monitored on a patterned wafer as it spun on the development module of a wafer track. Since the interference signal is generated from a circularly polarized light source, the DSM 100 has demonstrated robustness to the red cloud effect, developer spray, bubbles in the developer, and ambient light.¹

Two algorithms for the calculation of the in-situ development rate are proposed. After collecting the eight interference curves, these post processing algorithms used the Marquardt Levenberg non-linear regression algorithm and a linear regression approach to find the development rate as a function of development time. Although the standing wave effect was visible in the plots of development rate versus time using both techniques, the first approach generated the better curve. A plot of development rate versus depth was generated via numerical integration of the plot of development rate versus time.

Since the only equation used in the post processing algorithm is the interference relationship, this technique is equally well suited for other types of exposure and resist chemistries.

Possession of the in-situ development rate could provide further insight into resist development mechanisms, the development of better models, and the extraction of photolithography model parameters that are specific to the production process.

2.0 INTRODUCTION

In the past, the Perkin Elmer DRM has been used to measure the development rate of resist as a function of development time.³⁻¹⁰ Several limitations have prevented its broad acceptance. The DRM requires several different broad field exposures on a single wafer, samples the resist thickness interference with a single wavelength light source, and processes the wafer in a special tank for an immersion development. Since production wafer processing does not resemble the DRM wafer processing, the development rates calculated with the DRM are not representative of production.

A wish list for photolithography development rate measurements might look like this.

- 1) An in-situ measurement of the development rate of exposed regions on a patterned wafer.
- 2) A polychromatic sample of the resist thickness interference. Since the sensitivity of the resist thickness calculation oscillates as the interference curve oscillates, the error in the measured thickness can be very non-uniform. When the interference curve reaches either a maximum or a minimum, there is a range of resist thicknesses that can satisfy the interference equation. Conversely, along the steepest portion of the interference curve, the interference equation is able to converge on a single resist thickness. Hence, in order to obtain best results, several different wavelength interference curves should be collected simulta-

neously. In this manner, while one interference curve of a given wavelength may exist at a non-sensitive portion of the interference curve, the other wavelength interference curves will be sensitive and will compensate for the error in the first curve.

- 3) A robustness to ambient effects such as developer spray, bubbles in the developer, ambient light, and the red cloud effect.
- 4) Adequate sampling frequency.
- 5) Sensitivity to development nuances such as the standing wave effect and surface rate inhibition.
- 6) Calculation of the development rate versus depth for resist model parameter extraction.
- 7) Minimum modification to existing wafer tracks.

We propose a technique for the measurement of in-situ development rates that satisfies all of the above conditions. Using a Site Services DSM100, eight different wavelength interference curves were simultaneously monitored. Using this tool, one is able to measure the interference curves for the exposed regions of a patterned wafer as it spins on the development module of a wafer track. This tool has exhibited insensitivity to the above ambient effects.¹ The light interference can be sampled up to 40 times a second. For this work, virtually no modification of the GCA 9000 wafer track was required for installation of the DSM 100. In addition, the DSM 100 installation time was minimal.

The eight interference equations were assembled in two different post processing algorithms to generate the development rate versus time for several wafers. This plot clearly exhibits the standing wave effect and the surface rate inhibition. The plot of development rate versus time was then numerically integrated to generate the resist thickness versus time which is equivalent to the depth in the resist as a function of time. These two plots were then assembled to calculate the plot of development rate versus depth which is the form of the development rate models.

First, some model development is given to describe how the two post processing algorithms work. Next, some applications to conventional positive resist with an optical exposure, are provided to demonstrate its effectiveness. This is followed up with some conclusions for the measurement of the in-situ development rate.

This paper is the first in a two paper series on the extraction of process specific photolithography model parameters. The second paper, entitled, "Extraction of Process Specific Photolithography Model Parameters" follows this paper.

3.0 METHOD

Previous work on model parameter extraction centered around the development rates as measured on the immersion-based Perkin Elmer DRM. Perhaps a good first order indicator, the DRM lacked any of the development nuances such as development agitation due to the centrifugal forces of the development spinner and the development spray, the exact development time, and the dynamic microscopic developer composition. If possible, one would naturally prefer to extract the development rates from the development module, in-situ.

In this section, the approach employed for the extraction for the in-situ development rate is presented. Attractive to this technique is the independence of the extraction technique from the development mechanisms. This approach works equally well for many types of resists and with many types of lithography exposure (i.e. optical, e-beam, x-ray; contact, refractive projection, reflective projection).

Signal acquisition was performed through the use of the Site Services DSM 100. Although initially developed as an endpoint detection system, this tool monitors the thin film interference signal of the resist thin film from a circularly polarized polychromatic light source which may be converted to development rate.

The DSM system is comprised of three distinct elements, as shown in figure 1: the optical processing head(OPH), the signal processing unit(SPU), and a personal computer. The OPH sits above the wafer within the development cup module on the wafer track. A fiber optic cable runs from the OPH to the SPU and is multifurcated into eight cables before entering the SPU. From the SPU, converted data is loaded into the PC for data processing and operator interaction.

The OPH consists of tungsten halogen light source that is collimated and passed through a polarizing beam splitter. The light is then circularly polarized by passing it through a quarter wave plate before it strikes the wafer surface. An approximate one inch diameter beam of circularly polarized light is reflected from the resist coated and pattern wafer, parallel to, but aside from the axis of circular motion. The reflected light intensity is periodic with development as the thickness of the resist patterned images causes moments of constructive and destructive interference as a function of time. The reflected light is again passed through the quarter wave plate which causes only the circularly polarized light to become linearly polarized. The polarizing beam splitter reflects only the linear polarized light through a condenser lens and is focused onto a fiber optic bundle. The fiber optic bundle is then split into eight separate bundles each having a separate bandpass filter detector in the SPU. Signals output from the detector are then processed within the computer using the Site Services Lithacon software. The signal for the patterned geometries is isolated from the total signal (which includes the non-exposed region signal) by use of a Fast Fourier Transform (FFT) algorithm in the Lithacon software. It should be noted that spectrum of light used in the OPH was chosen to be outside of the range of absorbing frequencies of the resist.

There are a number of attractive features built into this system. The first of these is the obvious in-situ measurement. With little, if any modifications, the OPH can easily be added to almost any development cup. For this work, the OPH was mounted on a GCA 9000 wafer track at a distance of about eight inches from the wafer surface. This flexibility allowed easy access to the dispense nozzles and required no physical modifications of the development cup.

The second set of features are inherent to the circular polarization of the incident light and the isolation of that circularly polarized light before detection. Experimental results^{1,11,12} indicated a robustness in measurements to ambient light effects, scatter from resist sidewalls, aerosol droplets, suspended particles, bubbles in the developer and, for the case of static development, the "red cloud" effect. Red cloud is that term used to describe the opacity in the developer solution due to the presence of reacted resist in the developer solution.

In figures 2 through 9, the interference signal output from the Site Services DSM are provided for a wafer that was exposed with 90mJ/cm². It is clear to see that each of these curves was periodic in nature. However, the magnitudes of the peaks and valleys within a curve and between curves tended to be non-systematic. In order to implement a commonality between curves and within curves, peaks and valleys for each curve were identified or tagged and the signals were normalized with respect to their closest peak and valley to a value between -1.0 and +1.0. In this manner, a maximum could always be identified by a value of +1.0 and a minimum by a value of -1.0. The values of -1.0 and +1.0 were chosen such that a cosine function could readily be used in the subsequent development rate extraction. The corresponding normalized curve for figure 9 is shown in figure 10.

It was known from the superposition of the incident and reflected light that the resultant light should behave as a sinusoid. Specifically, the interference curve will oscillate as

$$S = \cos \left(\frac{4\pi n}{\lambda} Th \right) \quad (1)$$

where,

S = the interference signal,

n = the refractive index,

λ = the wavelength of the impinging light, and,

Th = is the instantaneous thickness of the resist.

Since the range of λ is relatively narrow, the refractive index was assumed to be constant. Cauchy coefficients could be used to find the appropriate refractive index as a function of wavelength.

In lieu of the absolute thickness, the instantaneous development rate and the thickness prior to Δt is inserted into equation 1, yielding,

$$S_i = \cos \left(\frac{4\pi n}{\lambda_i} (D\Delta t + do) \right) \quad (2)$$

where

Δt = the inverse of the sampling frequency,

i = the increment in measured wavelengths,

D = the development rate over the period Δt , and,

do = the thickness of the resist before Δt .

Using equation 2, for each increment of time, the rate that was required to produce the eight measured signals can be calculated beginning at the bottom of the resist/substrate interface where $do=0.0$. This form of the data is shown in figure 11. Here, a plot of the normalized signal versus wavelength is shown for a given increment in time. The sinusoidal nature of this curve, as predicted in equation 2, was apparent. Hence, one can solve for change in resist thickness over the period Δt which is equivalent to finding the development rate over Δt .

The Marquardt-Levenberg non-linear regression algorithm was used to iteratively solve for the instantaneous development rate. This algorithm minimized the Sum of Squares Error (SSE) between the measured and the calculated signal data as a function of wavelength for each increment in development time. The partial derivative of equation 2 with respect to the development rate is required with the Marquardt -Levenberg technique and is given in equation 3.

$$\frac{\partial S}{\partial D} = \frac{(-4\pi^2 n \Delta t)}{180\lambda} \sin\left(\frac{(4\pi n)}{\lambda} (D\Delta t + do)\right) \quad (3)$$

This approach has the advantage of minimizing the error in the direction of the measured data.

A second, analytical approach was used to calculate the development rate. Equation 2 can be rewritten as,

$$\cos(S_i) - \frac{4\pi n do}{\lambda_i} = D \cdot \left(\frac{4\pi n \Delta t}{\lambda_i}\right) \quad (4)$$

Equation 4 can solve for the development rate, D , analytically using linear regression, where D is the slope of the line and the intercept is zero. The solution for D using linear regression can be reduced to,

$$D = \frac{\sum_{i=1}^n \left(\frac{4\pi n \Delta t}{\lambda_i}\right)^2}{\sum_{i=1}^n \left(\cos(S_i) - \frac{4\pi n do}{\lambda_i}\right) \left(\frac{4\pi n \Delta t}{\lambda_i}\right)} \quad (5)$$

where,

n = the number of sampled wavelengths (in this case $n=8$).

Hence, equation 5 yields a much quicker calculation since it was able to avoid an iterative approach

With both approaches, for each increment in time, the instantaneous development rate was calculated. The added thickness in the resist for that increment in time was then added to do . In this manner, the development rate versus development time was readily extracted from the signal data. This plot was then numerically integrated with respect to time to produce the thickness of the photoresist at each of the sampled times. This was converted to the development rate versus thickness and development rate versus depth, which is the most important relationship for model parameter extraction.

4.0 APPLICATION

The above methods were then applied to wafers coated with about 1.2 μm of Shipley 812 resist, pre-baked at 100C for 45 sec, exposed with a test mask with G-line exposure, and post-exposure baked at 100C for 45 sec. Using the first, iterative approach, the plots of resist thickness versus development time, development rate versus development time, and development rate versus depth were generated as in figures 12 through 14 respectively. There was a 5.0 sec pre-wet before development, during which the DSM 100 sampling was hand-triggered to begin. The development used a continuous spray of MF312 developer. In these figures, the standing wave effect and the surface rate inhibition were readily apparent. Although the in-situ development rate calculation made no assumption about nature of the development rate as time progressed, the algorithm was clearly able to discern these subtleties. In addition, the thickness of the resist was calculated to be 1.16 μm which is close to the target thickness of 1.2 μm .

The accuracy of the instantaneous development rate near the bottom of the resist may be questionable. Looking at the interference plots in figures 2 through 9, all eight interference curves have a maximum at the resist/substrate interface. As the resist thickness increases, or the depth decreases, all eight curves remain nearly in phase until the resist is about 0.4 μm thick. Because these interference curves are in phase, if one were look at the interference signals across the wavelengths at a given instant, one would see a fairly constant value. Since there is little sensitivity looking across the wavelengths, the cosine function in equation 2 has difficulty in extracting the instantaneous development rate.

This point is evident in figures 15, 16 and 11. In figure 15 a plot of the normalized interference signal as a function of wavelength near the bottom of the resist was relatively flat. As the resist thickness increases (time in the development decreases), in figures 16 and 11 it was clear to see that the cosine function becomes more apparent, making it easier to extract the instantaneous development rate.

Inaccuracies in the cumulated thickness calculation are always compensated. When the interference reaches a maximum or a minimum, the cosine equation must have a given thickness in order to satisfy equation 2. Hence if development rate has been successively underestimated, when the calculations reach a minimum or a maximum, equation 2 must compensate and will tend to overestimate to make up the difference.

In figures 17 through 21 the plots of development rate versus time are given for sampling frequencies of 5, 8, 10, 20, and 40 times a second. The longer separation in sampling frequency is equivalent to integrating the interference curve over the period of separation, Δt . An improvement in the noise of the development rate curves is apparent as the sampling frequency decreases. The shape and integrity of curves do not appear to be compromised, even for the lowest sampling frequencies.

The reproducibility of this technique was explored by processing two additional wafers with the same set of conditions used for the wafer in figures 12 through 14. A plot of the development rate versus depth is shown in figure 22. The three wafers seem to have fairly reproducible results although wafer 1 seemed to have a slightly thicker resist.

A range of exposures was also examined. In figures 23 and 24, the thickness versus time and development rate versus depth were provided for exposures of 66, 90, and 114 mJ/cm². Both curves behaved as predicted with the lowest exposure energy resulting in the longest development time and the lowest development rate over the range.

The second technique did not yield as impressive a plot. In figure 25, the plot of development rate versus time using the second, analytical approach was less apparent. The standing wave effect was still detectable, particularly near the upper portions of the resist layer. However, this plot was not nearly as clear as the plots in figure 13. In addition, the resultant resist thickness that was measured to be 1.056 μm -- significantly less than the target thickness of 1.2 μm and the measured thickness of 1.16 μm from the first technique.

The poorer results from the second technique were attributed to the difference in minimized SSE. The largest source of random error in equation 2 is the measured signal, S . The first technique strives to minimize the error in the direction of S , since it is the response. In equation 4, the minimized SSE was in the direction of the two terms on the left side of the equals sign which is different than the direction of the source of error.

5.0 CONCLUSION

Two different algorithms were explored for the extraction of the in-situ development rate from the interference curves generated by the Site Services DSM100. The first technique, which was iterative in nature, yielded relatively clean plots of resist thickness versus time, development rate versus time, and development rate versus depth. The initial delay in development, the standing wave effect, and the surface rate inhibition were readily apparent in these plots. The total thickness of 1.16 μm was calculated with this algorithm, which is very close to the target thickness of 1.2 μm . This technique also appears to have good reproducibility. The DSM 100 is well suited for this type of analysis since it has demonstrated an acquisition of data that is robust to developer spray, the red cloud effect, and ambient light.¹

A second algorithm, which used a closed form for the development rate, produced a plot that was not as clear as the those generated using first algorithm. The discrepancy in the results has been attributed to the difference in the minimized SSE.

The data gather in this paper has a direct application to the extraction of process specific model parameters. The topic of photolithography model parameter extraction is addressed in the second paper of this two paper series which is entitled, "Extraction of Process Specific Photolithography Model Parameters."

6.0 ACKNOWLEDGEMENT

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Figure 1: A schematic diagram of the collection of interference curves using the DSM 100.

Figure 2: Measured signal vs dev. time for $\Lambda=700\text{nm}$

Figure 3: Measured signal vs dev. time for $\Lambda=767\text{nm}$

Figure 4: Measured signal vs dev. time for $\Lambda=800\text{nm}$

Figure 5: Measured signal vs dev. time for $\Lambda=830\text{nm}$

Figure 6: Measured signal vs dev. time for $\Lambda=840\text{nm}$

Figure 7: Measured signal vs dev. time for $\Lambda=900\text{nm}$

Figure 8: Measured signal vs dev. time for $\lambda = 930\text{nm}$

Figure 9: Measured signal vs dev. time for $\lambda = 960\text{nm}$

Figure 10: Normalized signal vs dev. time for $\lambda = 700\text{nm}$

Figure 11: Normalized signal vs wavelength (time=17.7 sec)

Figure 12: Resist thickness vs development time.

Shipley 812 PR, MF312 Dev., 90 mJ/cm² Exp., 100C 45sec prebake, 100C 45sec PEB.

Figure 13: Development rate vs time.

Shipley 812 PR, MF312 Dev., 90 mJ/cm² Exp., 100C 45sec prebake, 100C 45sec PEB.

Figure 14: Development rate vs depth in the resist.

Shipley 812 PR, MF312 Dev., 90 mJ/cm² Exp., 100C 45sec prebake, 100C 45sec PEB.

Figure 15: Normalized signal vs wavelength (time=30.225 sec ==> near endpoint)

Figure 16: Normalized signal vs wavelength (time=22.75 sec)

Figure 17: Development rate vs time for a sampling frequency of 5 times/sec.

Figure 18: Development rate vs time for a sampling frequency of 8 times/sec.

Figure 19: Development rate vs time for a sampling frequency of 10 times/sec.

Figure 20: Development rate vs time for a sampling frequency of 20 times/sec.

Figure 21: Development rate vs time for a sampling frequency of 40 times/sec.

Figure 22: Development rate versus time for three identically processed wafers.

Figure 23: Resist thickness versus development time for three exposures.
Shibley 812 PR, MF312 Dev., 100C 45sec prebake, 100C 45sec PEB.

Figure 24: Development rate versus depth for three exposures.
Shibley 812 PR, MF312 Dev., 100C 45sec prebake, 100C 45sec PEB.

Figure 25: Development rate vs time using the analytic solution to the development rate.