Specular Spectral Profilometry on Metal Layers

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With the advent of deep sub-micron semiconductor technology, metrology for metal interconnects becomes more critical. In addition to the line width, information about the height and the sidewall profile is needed to ensure good circuit performance. Conventional metrology tools such as CD SEMs and AFMs are either unable to measure the profile, or too slow for production process control.

Scatterometry is a promising candidate as an in situ, full-profile metrology tool [1]. In this method, scattering of broadband light (240 nm to 760 nm) on periodical structures is simulated by approximating the structure with a finite series of Fourier expansion terms [2]. By comparing the measured spectrum and the simulated spectra for various possible profiles in a pre-calculated library, the profile can be extracted. Previous work has shown good results on resist structures. For metal structures, however, more diffraction orders need to be included to accurately simulate light scattering. In this study, a library for 0.22 μm line and 0.44 μm space metal grating structures is generated using 31 orders. The profiles of metal grating structures of the same size are extracted using this library. Our data shows that the correlation between CD SEM and scatterometry-based profile extraction appears to be related to the sidewall angle of the profile. These discrepancies will be analyzed and discussed.

Keywords: Specular spectroscopic profilometry, DUV lithography, spectroscopic ellipsometry, metal layer metrology.

1. INTRODUCTION

As the semiconductor industry moves beyond 0.18 μm, process variation has an increasing impact on the features printed on the wafer, and metrology becomes more critical for process control. With continuing technology scaling into the deep submicron regime, interconnect constitutes an increasing portion of the overall circuit delay [3]. Not only line width, but also height and sidewall profile measurements are required to accurately characterize RC delay. (Figure 1)
Metrology is a key element in maintaining adequate process latitude for acceptable profile in lithography and etch processes. Accurate full-profile metrology is needed for characterizing and monitoring exposure, focus, post exposure bake (PEB), plasma etch, etc. Various techniques have been both proposed and implemented for measuring patterned features, such as visual test-based methods, atomic force microscopy (AFM), cross-sectional and top-down CD scanning electron microscopy (SEM), etc. These techniques are either expensive, time-consuming, destructive, or not accurate enough. Further, by their nature, they cannot be deployed in situ.

Optical metrology is a good candidate for overcoming the disadvantages of the metrologies mentioned above. Many methods have been proposed in this area. Kleinknecht and Meier used diffraction grating test patterns for monitoring linewidths on IC structures [6]. Damar, Chan, Wu and Neureuther used an automated HeNe laser spectrometer to explore the fundamental issues associated with nondestructive IC process monitoring by diffraction from drop-in test sites [7]. Tadros, Neureuther and Guerrieri used a massively parallel computer simulation algorithm to investigate electromagnetic scattering and optical imaging issues related to linewidth measurement of polysilicon gate structures [8]. Tadron et al in [8] did pioneering work in the area of using diffraction gratings as test structures, and a spectroscopic reflectometer as the data collection tool. They showed that the broadband reflectivity (diffraction characteristics) versus wavelength had high correlation to the grating features. All these methods intended to characterize the process based on the correlation between optical responses and process conditions, and they usually deliver effective linewidth values. However, no accurate profile information can be obtained from these methods.
Scatterometry is another optical diffraction technique based on the characterization of the diffraction grating structure from its optical diffraction responses. McNeil, Naqvi and co-workers have developed and demonstrated a single-wavelength, variable-angle scatterometry, or “2-θ” angle-resolved scatterometry [9]. This type of scatterometry utilizes angle-resolved measurements and characterization of diffracted light from periodic structures. Niu, Jakatdar, Bao and Spanos introduced Specular Spectroscopic Scatterometry / Specular Spectroscopic Profilometry (SSS/SSP), to measure the 0th order diffraction at a fixed incident angle and multiple wavelengths [1], [10]. This was the first technique that took the phase of the optical signal into consideration, in addition to the magnitude information. Due to its fixed angle, specular spectroscopic profilometry is easy to deploy. It can directly utilize conventional spectroscopic ellipsometers or spectroscopic reflectometers, and can be easily installed in situ or inline.

Previous work using SSP has shown good results on resist lines on poly layer [1], [10]. In this paper, we extend this work to resist lines on metal layers and etched metal features, and discuss some possible application to damascene process metrology.

2. SPECULAR SPECTROSCOPIC PROFILOMETRY

Specular Spectroscopic Profilometry measures the 0th order diffraction responses of a grating at multiple wavelengths. Diffraction response for the rest of the document will refer to both the magnitude and phase of the diffracted signal in the case of an ellipsometer, and just magnitude in the case of a reflectometer. Given the 0th order diffraction responses, one can then attempt to reconstruct the grating profiles. Conventional spectroscopic ellipsometry and reflectometry equipment can be used.

A spectroscopic ellipsometer is used in this work for measurements of 1D gratings. The ratio of the 0th order complex transverse electric (TE) and transverse magnetic (TM) reflectivity \( \rho = r_{p,0} / r_{s,0} = \tan \Psi e^{i\phi} \) is measured, where \( r_{p,0} \) is the 0th order TM reflectance coefficient and \( r_{s,0} \) is the 0th order TE reflectance coefficient.

The extraction of a CD profile can be viewed as an optimization problem. The objective is to find a profile whose simulated diffraction response matches the actual measured response. For practical inline usage we propose a library-based methodology for CD profile extraction. Details of this method can be found in [11].
3. EXPERIMENTAL RESULTS AND DISCUSSION

In the first experiment, photoresist features on metal films were measured using specular spectroscopic profilometry. The stack is developed resist on anti reflective coating (ARC) on thin film layers, which consist of TiN on Al on TiN on Ti on TEOS, as shown in Figure 2. The feature we study is a one-dimensional grating, with line/space of 0.22/0.44 \( \mu \text{m} \). The grating area under test is 250 \( \mu \text{m} \) by 250 \( \mu \text{m} \).

![Figure 2. Stack layer for patterned resist features on metal thin films.](image)

A focus exposure matrix (FEM) is printed on Shipley's UV6 resist using ASML DUV stepper. Focus was set from –0.4 \( \mu \text{m} \) to 0.2 \( \mu \text{m} \) with a step of 0.15 \( \mu \text{m} \), and exposure doses were set from 21.9 mJ/cm\(^2\) to 29.1 mJ/cm\(^2\) with a step of 1.2 mJ/cm\(^2\). After exposure and PEB, the resist is developed. A KLA-Tencor 1280 spectroscopic ellipsometer is used to measure the response (the ratio of the 0\(^{th}\) order TM and TE reflectance) at an incidence angle of 70°. Twenty-two dice were measured, and the extracted resist profiles are shown in Figure 3 in the same layout as they are on the wafer. The profile distribution across the wafer looks quite reasonable for an FEM.

We also performed CD SEM measurements on these gratings, and compared the bottom CD measurement produced from SSP and CD SEM, as plotted in Figure 4. The two data sets show good correlation. The deviation is mostly due to the constant offset for the CD SEM, which is a well-known phenomenon. Some of the deviations between the two metrologies are not consistent with others. Upon further examination, we found that those deviations correspond to profiles that have small sidewall angles or some footing, which makes CD SEM measurements problematic.
Figure 3. Extracted FEM resist profiles plotted as their positions on the wafer. All figures are in the same scale. The numbers on the upper right corners are site numbers.

Figure 4. Comparison of profilometry and CD SEM bottom CD.
The FEM was then patterned onto the metal layer using plasma etching, and the resist and ARC were removed. The resulting stack of patterned metal features (TiN on Al on TiN on Ti) on TEOS thin film on silicon wafer is shown in Figure 5.

![Figure 5. Stack structure for patterned metal features.](image)

![Figure 6. Extracted FEM metal profiles plotted as their positions on the wafer. All figures are in the same scale. The numbers on the upper right corners are site numbers](image)
The KLA-Tencor ellipsometer was used to measure the response from the metal gratings. Again 22 dice were measured and the profiles were extracted, as shown in Figure 6. CD SEM measurements were also made, and the comparison of top CD from both methods is plotted in Figure 7. We can see that the deviation between CD SEM and profilometry is more consistent than the result for resist features in Figure 4, because the sidewalls for the metal profiles are fairly straight compared to those for the resist profiles. We also note that the SEM charging effect which can distort photoresist measurements is much less significant when measuring metal features. This helps the CD SEM get more consistent results.

To study the effect of sidewall angles on CD SEM measurements, we take our spectroscopic profilometry as the reference, and plot the deviation of CD SEM measurement versus sidewall angle, as shown in Figure 8. We can see that for smaller sidewall angles, the distribution of deviations between the two metrologies is larger. This might be because the CD SEM algorithm cannot easily determine top/bottom boundaries when the profiles are not very steep.

Figure 7. Comparison of profilometry and CD SEM top CD for metal features. CD SEM has no valid measurements at the missing data points
4. PROPOSED APPLICATION FOR DAMASCENE PROCESS METROLOGY

Damascene processes bring a new, difficult challenge to CD measurement and end point detection. Several methods have been proposed based on CD SEM [12]. One is to measure CD on the dielectric lines, but this suffers from sample changing effect. Another approach is to measure the dielectric trench structure after the barrier layer is deposited. Although this would reduce the charging problem, sidewall shapes could not be characterized, and the electron beam may damage the dielectric layer.

Figure 8. Deviations between CD SEM and profilometry bottom CD vs. sidewall angle.
Specular spectroscopic profilometry is a promising candidate for measuring trench profiles with or without metal filled in. It can also be used for end point detection during the CMP process, as illustrated in Figure 9. As the metal layer is being polished, the response from the structure can be measured using ellipsometry or reflectometry. At first, the signal is much like that from metal film, because most of the light going through has been absorbed. When the metal layer is getting thinner, it becomes more transparent, and the scattered light from the structure below can be detected. If the metal film thickness is included as a variable in the library [ref], the remaining film thickness can be measured and used for end point detection.

5. CONCLUSIONS

Specular spectroscopic profilometry is used to measure resist features on metal films and etched metal gratings. Full profiles of an FEM for these two structures have been extracted and good correlation with CD SEM was achieved for traditional metal structures due to better sidewall angle and less sample charging effect. We plan to test, demonstrate and use the metrology for metal line profile measurement and end point detection in the damascene process.

Figure 9. Typical 1D grating for monitoring damascene processes.
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REFERENCES


