Addressing thin film thickness metrology challenges of 14nm BEOL layers

Zhiming Jiang, Ronny Haupt, Carlos Ygartua, KLA-Tencor Corporation, One Technology Drive, Milpitas, CA 95035, USA

Alok Vaid, Michael Lenahan, Vijayalakshmi Seshachalam, GLOBALFOUNDRIES, 400 Stone Break Road Extension, Malta NY 12020, USA

***Abstract*— In this paper we discuss the impact of these two effects on the film thickness measurement and describe our approach to develop a film stack model and recipe which accounts for the underlying stack as well as Chemical Mechanical Planarization (CMP) variation. We also describe the verification and production implementation of this model using mass production data.**

Keywords—Spectroscopic Ellipsometer, Chemical Mechanical Planarization (CMP), Film stack

I. INTRODUCTION

Film thickness metrology in the Back-end-of-line (BEOL) metallization process flow has been well established over the past years and nodes. As a result of scaling towards smaller design rules[1], film thickness metrology throughout the process flow is mainly challenged by new materials, and stacks with more layers and/or decreasing thicknesses. This leads to tighter requirements on metrology precision, repeatability, and tool-to-tool matching.

In the case of BEOL layers additional challenges are arising at the 2x nm node and below related to the basic physics of the ellipsometer or reflectometer measurement which are typically used and its assumptions about the film stack model. At larger design rules, the metal thickness of the metallization materials was large enough to act as a virtual substrate for the model-based measurement, i.e. the broadband light which is used for such measurement does not interact with materials below the metal layer. As the metal thickness becomes thinner, the measurement becomes sensitive to the underlying stack, and therefore the model needs to account for it which adds an additional level of complexity.

In addition, at the 2x and 1x nm nodes, the variation of the chemical mechanical planarization process (CMP) becomes more pronounced and optically visible to the measurement as the metal thickness itself gets thinner. The effects of CMP dishing need to be accounted for in the measurement model [2], because the thickness measurement is typically performed on a relatively large pad in the scribe line where this effect is more pronounced.

In this paper, we will present an approach used to model the change of Cu film properties and make proper method for low-k film thickness measurement at each CMP step.

Spectroscopic ellipsometry (SE) is a fast, non-invasive metrology technique that is widely used in semiconductor manufacturing. The work discussed in this paper used KLA-Tencor Aleris series tool. Its wide SE wavelength range (from 150nm to 800nm) and other combined measurement subsystems (like a UV reflectometer and single wavelength ellipsometer) enable the users to choose appropriate measurement system best suited for specific applications. In this study, The SE subsystem with the wavelength ranging from 240nm to 800nm was used.

The BBSE technique on Aleris uses a broadband spectrum light source [3]. For measurements, broadband light of wavelengths between 150nm to 800nm can be used. This light is linearly polarized and focused on the wafer surface at an oblique angle. To characterize polarized light, the electromagnetic field perpendicular and parallel relative to the incident plane are used; E_s and E_p respectively (see Figure 1).

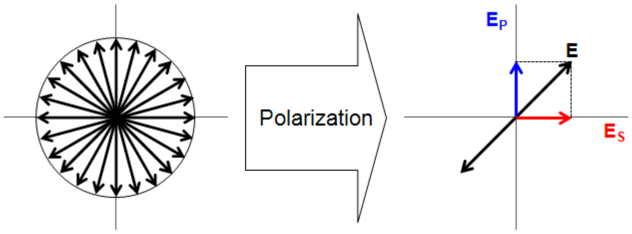

Fig. 1. Orientation of randomly (left) and linearly polarized light (right)

Upon interaction with the wafer surface, a fraction of the polarized light will be reflected. The remaining light gets refracted into the film stack and interacts with underlying layers through reflections and refractions at each material interface. Ultimately, the refracted fraction then exits the film stack again and overlaps with the reflected fraction of the light. The fractions of reflected versus refracted light vary greatly between E_s and E_p. As a result, a phase shift Δ between E_s and E_p is introduced (commonly noted as $Cos\ \Delta$). Furthermore, the amplitude change due to interaction with the film stack also varies between E_s and E_p. The resulting ratio is characterized as $Tan\ \Psi$ (1).

$$E_p / E_s = Tan\ \Psi \tag{1}$$

The values of the resulting ellipsometric parameters $Cos\ \Delta$ and $Tan\ \Psi$ depend on the thicknesses, refractive index n and extinction coefficient k of the individual layers of the measured stack. It has to be noted that both n and k are wavelength-dependent material properties, resulting in $Cos\ \Delta$ and $Tan\ \Psi$

also being functions of wavelength. The broadband spectrum being used allows the measurement of *Cos Δ* and *Tan Ψ* over a wavelength range.

The link between measured spectra and film stack characteristics, i.e. layer thicknesses (T) and optical properties (refractive index n, extinction coefficient k) are theoretical models. These models can be purely mathematical (e.g. Cauchy polynomials), but more commonly are of physical nature. Based on these models and using appropriate seed values for all model parameters, a set of theoretical *Cos Δ* and *Tan Ψ* spectra can be calculated. Selected model parameters are then iteratively floated to fit the theoretical spectra to the measured spectra over the entire wavelength spectrum. Once the best fit is found, T, n and k can be derived from the model and reported as measured parameters. As a quality metric of the goodness of fit between theoretical and measured spectrum, the spectral fit is qualified by the normalized goodness of fit (NGOF). This parameter is less sensitive to negligible variations in optical path and material properties. It can assume values between 0 and 1, the former being poor fit and the latter being perfect fit.

The scope of the work on BEOL Copper (Cu) CMP stacks consisting of a Low-k material on BLOK on the Cu metal layer was to stabilize the measurement which was impacted by Cu thinning and dishing effects on the measurement pad. A proper modeling of Cu dispersion is the key element to be successful in the SE measurement

Previously, due to the described effects on the Cu pad, measurement recipe was tailored at different steps to accommodate the Cu effects. This increased the number of metrology recipes required for similar layers. For some SE metrology steps the recipe was not sufficient to provide a reliable measurement. The more efficient way for this CMP film stack monitoring is to use one recipe to cover all CMP steps with stable and reliable results. As expected, the major issues found to achieve that have been to accommodate the change of Cu thickness across the wafer, esp. towards the wafer edge due to non-uniform polishing, dishing effects, and signals coming from the underlayer stack. All of those effects can be reflected in the dispersion model for Cu.

The key element of the work was to develop a dispersion model that can accommodate the changes of Cu. To effectively model the material dispersion of Cu, a Bruggeman Effective Medium Approximation (BEMA) [4] dispersion model was used. In the case described here, a BEMA model consistent of 18 components was applied. The BEMA components were chosen at normal and extreme conditions where the vast change in Cu dispersion and CMP artifacts could be accounted for.

II. RESULTS

The film stack described in this work is Cu\Blok\Low-K with the thickness of Blok and Low-K being the parameters of interest. The stack repeats as the metal stack is built up to 7 metal layers (Mx).

When Cu thickness is thick (e.g, 600 Å or above), the Cu layer can be treated as substrate so each repeat stack of Cu\Blok\ULK can be modeled simply as Blok\ULK on Cu substrate without worrying the film stack information underneath Cu from previous stacks would pass through top Cu layer to influence the top Blok\ULK measurement. The effect of Cu layer thickness is assessed with simulation of a complex stack containing Si\TEOS\NITRIDE\TEOS\BLOK \ULK\CU\BLOK\ULK multi-layers. Figure 2 shows the result of Cu thickness effect on the overall fitting quality with the change of underneath Blok\ULK information, for a typical Cu dispersion and Blok\ULK stack. In the figure, the thickness of ULK thickness is varied from -300Å to the nominal thickness (center at 0, where fitting error is minimum) and to 300Å. For Cu thickness thicker than 600Å, the fitting error variation is around 40 or smaller, that is similar to the typical fitting error from SE measurement system in a real measurement for such complex stack. The fitting error contributed from the information under Cu layer can be negligible. The complex Cu film stack can be simplified as Cu\Blok\ULK only to measure the thickness of top two layers. When the Cu thickness is getting thinner, the fitting error starts to increase significantly and the stack information under Cu layer will have non-negligible contribution and the information underneath Cu has to be taking into account into the stack modeling to accommodate the variation of stack under Cu.

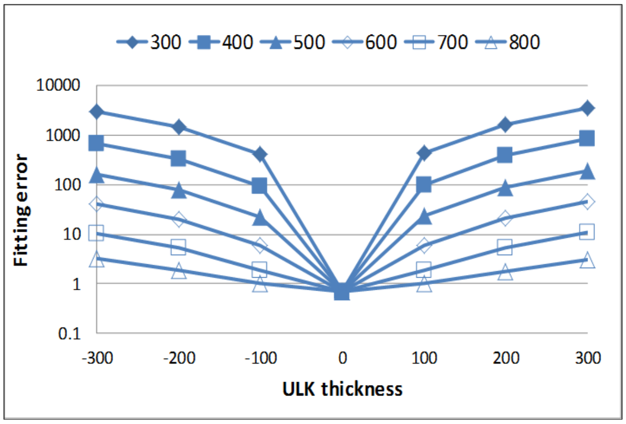

Figure 2. The fitting error variation with Cu thickness (from 300Å to 800Å). The ULK thickness is varied from -300 Å A to 300Å from the nominal thickness.

When the stack information under Cu is non-negligible, the proper treatment of Cu and underneath information is crucial for a stable and accurate measurement of such stack. For the production monitoring point of view, a single measurement recipe should be able to cover all those repeat metal stacks for easy monitoring and recipe maintenance.

Several experiments to characterize the Cu dispersion and underneath stack effects at different CMP steps have been used.

First, a set of design of experiment wafers was prepared at different CMP conditions and the measurements were made following the CMP steps so the changing of Cu and underlayer equivalence could be addressed. Then the initial Cu dispersion BEMA model was developed by working on the stack at different CMP stages for the same set of DoE wafers.

Second, by collecting measurement results with real production lots at different CMP steps, the initial model was put into offline process software to fine-tune the dispersion model and to accommodate for actual process variation at different CMP stages. With proper choice of the BEMA fraction components and algorithm settings, one measurement recipe was finally developed to cover all the steps over CMP process from M1 to M7.

Finally, the measurement recipe was implemented on the Aleris tools and to monitor real production lots for the final verification.

Some Cu dispersions used in the final Cu BEMA model are shown in Figure 1. The combination of Cu thickness thinning effect, film information coming off the underlayer and dishing effects due to CMP are contributing to the unphysical dispersion curve form compared to traditional Cu dispersions.

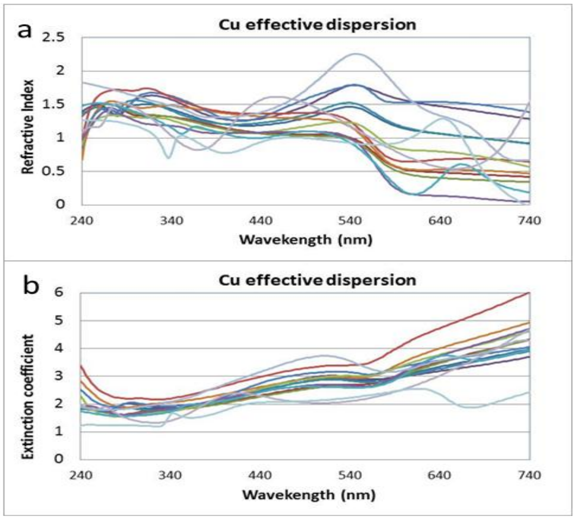

Figure 1. Cu dispersion used in the BEMA dispersion model: a) refractive index and b) extinction coefficient.

For SE measurements, the fitting quality indicator Goodness of Fit (GOF) is a representation for the measurement quality. It quantifies the spectral fit quality between a measured spectrum and the modelled spectrum. The comparison of the measurement recipe used previously and the newly developed recipe on one of DoE sample is shown in Figure 2. The film thickness (low-K, blok) distribution across the wafer radius is plotted, along with fitting NGOF (normalized GOF). The CMP process is usually causing a top thickness distribution that is radial symmetric. However, as expected, the Cu thickness at the wafer edge was lower than in the center area. This was confirmed with independent reference measurement. The NGOF is significantly dropped due to this effect. At the same time, the Blok film thickness showed abnormal large variation at the wafer edge.

With the proper modeling of the Cu dispersion, the new recipe is able to accommodate the complex change in Cu and provide consistent NGOF across the wafer, and hence more reasonable thickness measurement result distribution.

The comparison of measurement with old recipe and new recipe on DoE was presented in Table 1, where within wafer uniformity of three DoE wafers with different low-K (ULK) thickness split conditions at uncured and cured on low-K was compared. Clearly, for all DoE wafers, the old recipe has huge variation of fitting quality NGOF, which indicates the low fitting quality, or low measurement confidence sites existence on all samples. As shown in figure 2, those sites were generally at wafer edge where Cu thickness is thinner due to uneven CMP process. For new recipe, the Blok thickness variation is much smaller than those from old recipe.

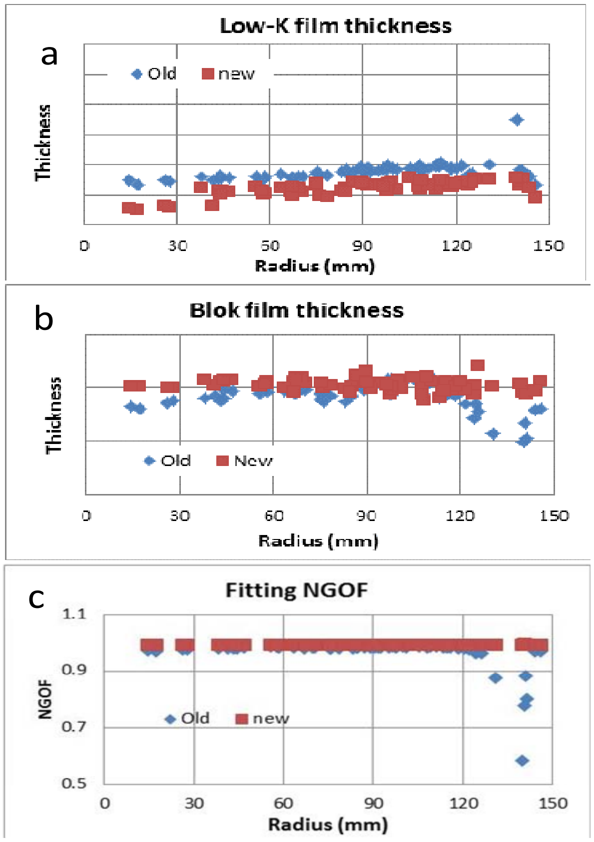

Figure 2. The measurement results for one DoE sample with old and new recipes: a)low-K thickness variation vs. radius; b) Blok thickness distribution vs. radius; c) fitting NGOF distribution vs. wafer radius.

Table 1: Within wafer uniformity (3sigma of 64 sites per wafer)

Condition	Wafer	Old recipe			New recipe		
		T_Blok	T_Low-K	NGOF	T_Blok	T_Low-K	NGOF
Uncured	wafer 1	69.69	84.79	0.1851	16.90	73.88	0.0003
	wafer 2	58.56	91.11	0.1745	14.95	132.55	0.0002
	wafer 3	57.84	70.19	0.2716	27.25	151.53	0.0005
Cured	Wafer 1	12.86	114.62	0.3484	25.91	59.46	0.0023
	Wafer 2	58.58	80.60	0.1009	26.23	98.85	0.0007
	Wafer 3	70.54	68.56	0.1436	26.23	98.85	0.0007

Table 2: Repeatability of wafer mean (9site per wafer)

Condition	Wafer	Old recipe			New recipe		
		T_Blok	T_ULK	NGOF	T_Blok	T_ULK	NGOF
Uncured	wafer 1	1.29	0.42	0.0033	0.26	0.50	0.0000
	wafer 2	0.74	0.78	0.0001	0.39	0.58	0.0000
	wafer 3	0.70	0.80	0.0004	0.22	0.55	0.0000
Cured	Wafer 1	0.16	0.35	0.0007	0.08	0.08	0.0000
	Wafer 2	0.47	0.30	0.0001	0.16	0.35	0.0000
	Wafer 3	0.50	0.54	0.0001	0.13	0.67	0.0000

However, both old and new recipes have similar performance on repeatability, as shown in Table 2, where

3sigma of wafer mean for 5 times load/unload is compared with 3sigma of wafer mean.

The new recipe has been applied on the same device but at different CMP steps (from M2 to M7). Figure 3 shows one product monitoring results of Blok and low-K thicknesses and NGOF values of wafer mean at different steps (M2 to M4) and the comparison with previous recipes. 21 sites per wafer were measured for this experiment.

It may be worthwhile to mention that the previous monitoring scheme involved several recipes that were tailored to particular CMP steps to accommodate film changes. So the results presented in Figure 3 are from several old recipes. However, for the new recipe, it can cover all CMP steps for current 2x technology node measurement needs.

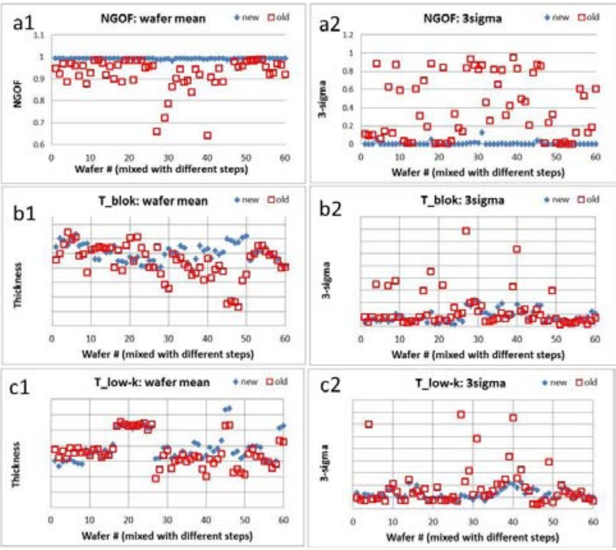

*Figure 3. Wafer mean and 3sigma of NGOF, Blok and low-K thickness for the same product but at different CMP steps: a1) NGOF; a2)3sigma (3*standard deviation); b1) Blok thickness; b2)3sigma of Blok thickness; c1) thickness of low-K film and c2) 3sigma of low-K film thickness. X-axis is the wafer number measured at different CMP steps.*

The new recipe has improved variability of NGOF from wafer to wafer, as shown in Figure 3a1. It shows smooth fitting quality of each wafer at difference steps, and the NGOF is around 1. It clearly indicates that the new method is able to cover the variation of CMP at different steps and the recipe generates stable and reliable measurement results. The within-wafer variation of NGOF, shown in Fig. 3a2 as 3sigma, is close to 0, which indicates the fitting quality at each site of wafers is almost equal. For old recipes, however, there is quite large number of sites with low fitting quality (low NGOF). Those low NGOF sites would cause confusion to processing engineers as it may be difficult to judge what causes low NGOF: process or measurement.

Accordingly, the Blok and low-k thickness variation within wafer as well as from wafer to wafer is smoother and matches the process expectations, which indicate the new recipe has similar sensitivity to the process variation. In comparison, the results with the previous recipes show very large variation in NGOF and some thickness excursion are much larger than acceptable process specification, and would have resulted in false alarm for the process.

III. SUMMARY

In this paper, we described a method to effectively monitoring film stack at different metal CMP process steps in the semi-conductor manufacturing using the KLA-Tencor Aleris spectroscopic ellipsometer metrology tool. By proper modeling of the Cu dispersion and simulating the underlayer film information underneath the Cu pad, a single measurement recipe was developed which can be used to monitor each process steps in the metal CMP process with stable and reliable results.

For more advanced process nodes, as Cu thicknesses continue to become thinner, this work and the approach taken are expected to become even more relevant.

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