

# High Precision Thin Metal Film Measurement by Optical Transmission

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## Abstract

Recent development of new products has given rise to stringent requirements for precision deposition control of thin metal films. Enhancement mode (E-mode) pHEMT devices require a very thin layer of platinum (Pt) in the range of 25 to 200Å to form the base of the gate contact. Furthermore, the ohmic metal needs to have each of the constituent layers deposited precisely. In these applications, thickness variations of as little as 5Å will result in detectable device performance shift and probe yield loss. A typical E-beam evaporator employs a crystal monitor for deposition control and film thickness is measured using a profilometer. The accuracy of the step height measurement diminishes with decreasing thickness below about 300Å. This paper described how we applied optical transmission to measure thin metal films. The optical technique enabled us to match the coating thickness of two evaporators to within 3Å. The procedure described in this paper has facilitated quick development of the deposition process and allowed a prompt transition to production.

## INTRODUCTION

The profilometer is the most commonly used metrology tool for measuring metal film thickness. The instrument utilizes a stylus that travels over a metal film step on a substrate. Operating on a mechanical measurement principle, the result is influenced by many factors. When measuring a very thin film on the order of tens of Angstroms, the profilometer has reached the precision limit and the measurement is increasingly drowned out by substrate roughness and ambient noise.

The limitation of the profilometer has not been an issue until we need to transfer the E-mode product to production evaporators. Despite our meticulous effort to calibrate the tooling factors, there was always a parametric disparity between deposition tools. Figure 1 showed the contact resistance ( $R_c$ ) comparison of a split lot between two tools.  $R_c$  is sensitive to the ohmic metal composition. Even a difference as small as 10Å in film thickness can affect  $R_c$  values.

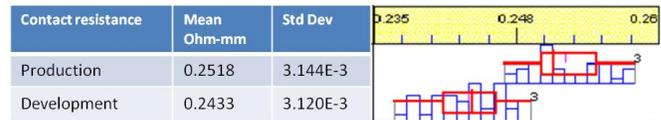


Figure 1 Ohmic contact resistance difference, however slight, between two tools.

E-mode devices can employ a platinum (Pt) buried gate to fulfill the positive threshold needed for a normally off state operation. The device threshold voltage ( $V_{th}$ ) is very sensitive to the thickness of the Pt layer and can vary by up to 20 percent with a 5Å change in Pt thickness. This is a considerable variation and will affect  $V_{th}$  control. Successful production of an E-mode device relies on a metrology capable of resolving film thickness close to one atomic layer (~2.7Å). It is apparent that a new approach needs to be considered.

## OPTICAL TECHNIQUES

Optical metrologies are used in any semiconductor fabrication facility for characterizing silicon nitride, oxides, and other dielectric films. They include ellipsometry, reflectometry and, perhaps less frequently used, transmission.

Although optically opaque, metals, when deposited in a very thin layer, have optical properties of an absorbing film thus making it feasible to apply optical measurements on metal films up to several hundred Angstroms thick. Unfortunately, the optical constants for thin metal films ( $n$  and  $k$ ) vary significantly with thickness, deposition condition, and microstructures. This presents immediate complexity for both ellipsometry and reflectometry unless the optical constants for the specific film are known. Spectroscopic ellipsometry, therefore, must be used in conjunction with transmission to generate absolute film thickness [1], [2], [3].

Optical transmission, as the name implies, detects the intensity that a light beam transmits through a medium. Like ellipsometry and reflectometry, transmission alone cannot produce absolute thickness value. It can, however, be used effectively to compare two metal films deposited with the same technology and under identical process conditions. This makes transmission very desirable for applications such as tool matching and process transfer where the primary goal is to have the production tools faithfully reproduce an

identical film as the development tool. Moreover, if absolute thickness is desired, multiple FIB/STEM samples of different thicknesses may be used to calibrate the intensity, which would allow the absolute value to be derived in great precision. However, this paper will address the tool matching aspect of this application.

#### SAMPLE PREPARATION

A Woollam Alpha SE ellipsometer, which was equipped to operate in transmission mode, was used for this work. We used soda lime glass 620 $\mu\text{m}$  thick cut into 100mm semi-standard wafer dimension. The glass wafers were cleaned in Standard Clean 1. The 20-minute process removed any surface contaminants that could otherwise distort the transmission results. A jig, as shown in figure 2, was machined to hold the glass wafer vertically during measurement so that the light beam incident angle was normal to the wafer.

#### PROCEDURE

The E-mode process was developed in a Temescal FC2800 evaporator. The production tools were newer vintage of the same model. Once the E-mode process was developed, samples were sectioned by FIB/STEM to examine the actual film thicknesses. They served as our reference against which the production tool will compare. Since the uniformity of these tools had already been optimized and determined, we used two glass wafers in each run - one in the inner and one in the outer tier. Should this procedure be incorporated as part of the tool qualification process, a minimum of six wafers strategically spread out in the wafer dome to capture the across-the-dome uniformity is recommended. To eliminate the variations caused by the rotating substrate holder, the same wafer positions were used for the experiment.

To deposit a very thin film, it is imperative for the dome to rotate at a high RPM. We have found 20 RPMs to be the minimum for a 50 $\text{\AA}$  film for uniformity and process consideration. On the other hand, the deposition rate needs to be low to allow sufficient revolution of the dome for the duration of the deposition. We used 1 $\text{\AA}/\text{sec}$  in this work.

Zeroing of the Woollam Alpha SE was carried out by running a scan without any wafer in the path of the light beam. Plenty of warm-up time is essential for the lamp to stabilize after initial power up.

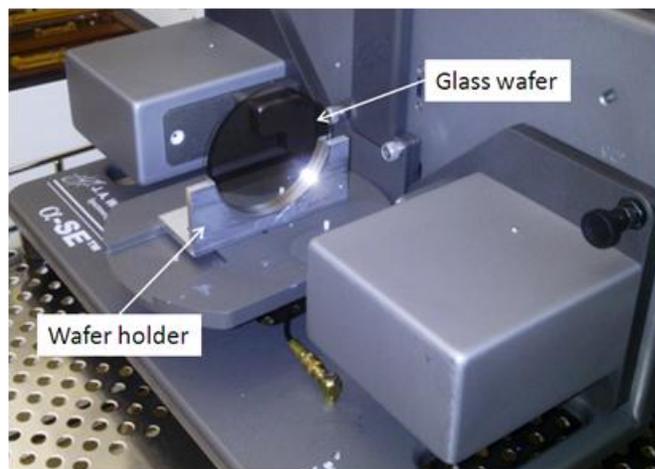


Figure 2 Woollam Alpha SE ellipsometer in transmission mode with wafer holder.

Our tooling factor calibration procedure comprised of many 2,000 $\text{\AA}$  runs on blank wafers. After each run, 15 sites were measured per wafer on a Tencor P15 profilometer. The shaper mask was trimmed based on the thickness profile to achieve optimum across-dome uniformity. Once the calibration process was completed, a 50 $\text{\AA}$  nickel (Ni) film was deposited in both the development tool and the production tool.

#### RESULTS

Despite the painstaking effort to calibrate the tooling factors, transmission measurement showed a difference. The wafers that ran in the production tool had lower intensity compared to the development tool implying a thicker film. See figure 3.

In transmission mode, the Woollam Alpha SE covers the entire visible spectrum from 400 to 900nm. The intensity is a unit-less normalized value. Over a wide thickness range (a couple of hundred  $\text{\AA}$ ), intensity does not correlate linearly. However, for a small intensity delta, we can treat it as such.

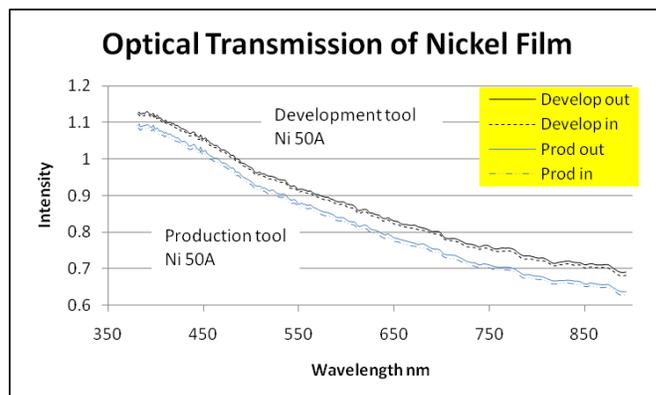


Figure 3 Optical transmission of nickel films (50 $\text{\AA}$ ).

Summarizing the intensity by average, we could easily see that the production tool had 0.0420 lower intensity compared to the development tool. It is interesting to note that the intensity difference between the inner tier and outer tier is 0.0073 for both tools, which would indicate that both tools have the same excellent uniformity.

In the tooling factor calibration process, the difference between the inner and outer row was found to be about 2Å for Ni. Based on this data, a 3Å reduction to the production tool was made. The intensity difference decreased to 0.0200 as a result but it was not in perfect alignment yet. To show the intensity difference more clearly, the wavelength and intensity scales of figure 4 and 5 have been expanded.

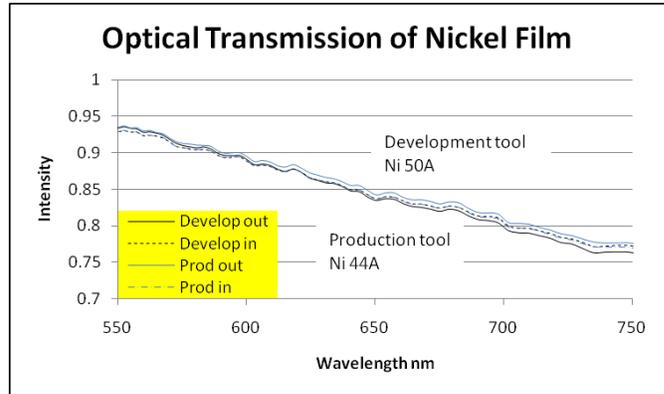


Figure 5 Optical transmission showed perfect matching of production to development tool,

Equipped with this technique, which allowed us to discern Angstroms of difference in film thickness between deposition tools, split lots were repeated. Parameters sensitive to metal thickness variation were compared. Contact resistance showed no difference in parametric value or in distribution. See figure 6

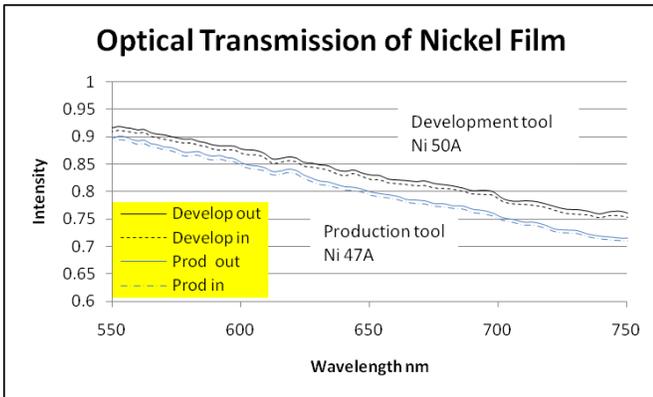


Figure 4 Comparing optical transmission spectrum of nickel films (47Å and 50Å).

After evaluating the average intensity of the 50Å and 47Å films, we made another 3Å reduction to the production tool, and the resulting spectra overlapped indicating perfect matching of the two nickel films. From this experiment we learned that in order to produce a 50Å Ni film in the production tool, the recipe set point needed to be 44Å - a 6Å difference. In addition, we can conclude that 3Å of evaporated Ni film corresponded to an average intensity delta of 0.0200. If there is a need to match another production evaporator, this correlation is directly applicable.

This process was repeated for each of the metals used in the critical layers including Platinum, Germanium, and Titanium. Typically two iterations were required to achieve perfect alignment. The first attempt was to probe the intensity delta for a given thickness change. The second iteration will usually complete the matching process. The prerequisite, being the standard tooling factor calibration procedure, has been correctly performed. Once the tooling factors have been established, fine adjustment in the very thin thickness range should be made in the recipe thickness set point, and not via tooling factor.

Contact resistance	Mean Ohm-mm	Std Dev	0.205	0.218	0.23
Production	0.2195	5.052E-3	[Box plot]		
Development	0.2199	4.106E-3	[Box plot]		

Figure 6 Contact resistance of split lot after tool matching using transmission.

Other critical parameters including  $V_{th}$ ,  $R_{on}$  and  $I_{dss}$  were practically identical to the wafers that ran in the development tool. The mere Angstroms of difference in film thickness have been causing the parametric variations. The application of transmission measurement has enabled the successful release of the E-mode process.

A 1000Å Au film was used to find the thickness limit below, in which sufficient intensity remained for accurate measurement. The Au transmission spectra (figure 7) has a characteristic peak at 500nm. Overall transmission is much reduced at 1000Å, and it is probably at the boundary for reliable measurement. Transmission data showed the two tools in exact agreement with the intensity difference between the two sets of sample smaller than the across-dome variation of either tool.

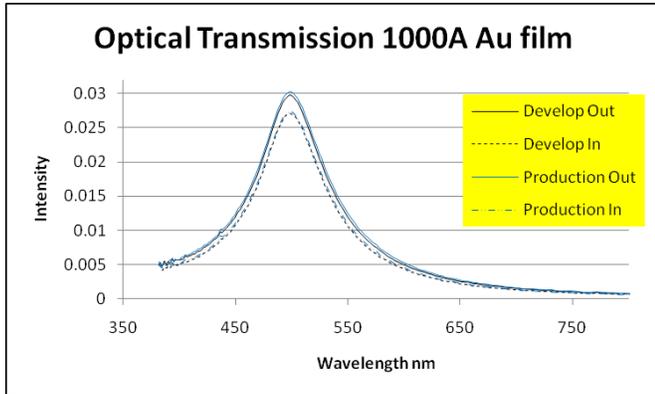


Figure 7 Transmission spectra of 1000Å Au film.

The results confirmed the accuracy of the profilometer and the tooling factor calibration process on films thicker than 500Å. Film thickness in this regime may be measured by either profilometry or transmission and the two technologies serve to validate one another. Films thicker than 1000Å can be precisely measured on a profilometer.

#### THEORY

When depositing a very thin film in the tens of Ångstroms range, there could be a variation of up to 15 percent (8Å) between tools. The discrepancy came from differences in tool geometry, hardware, and software set up that are distinctive to each tool. The differences, which include shutter transition and deposition overshoot, are small and are independent of the film thickness. To compensate for these differences, corrections should be made to the recipe thickness set point instead of the tooling factors assuming standard calibration procedure has been performed and the correct tooling factors established.

#### CONCLUSION

Considering substrate roughness, ambient noise, and other factors, a profilometer measurement can only guarantee roughly 50Å accuracy. Transmission is a precise measurement for thin metal films from Angstroms up to about 800Å. The actual limit depends on the properties of the particular metal. Optical transmission is a useful technique to match a new tool to a known standard. For this application, absolute thickness value is less critical but precision matching is of utmost importance. This metrology technique fills the gap of profilometry in the thickness range below 800Å. Ellipsometers reside in nearly all wafer fabrication facilities and modern versions are often equipped to measure transmission as well. In addition to its precision, it is also a cost-effective solution since no capital investment is required. We have demonstrated successful application of transmission to match two tools to within 3Å in a relatively short period of time.

#### ACKNOWLEDGEMENT

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