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Thin Film Measurement Systems

Updated: April. 14,2009

Measurement Guide
Thin-films measurement using Reflectance or/and Transmittance spectroscopy

It is easy to be a measurement expert with TFCompanion

The Purpose

This document describes the measurement procedure and basic use of TFCompanion software.

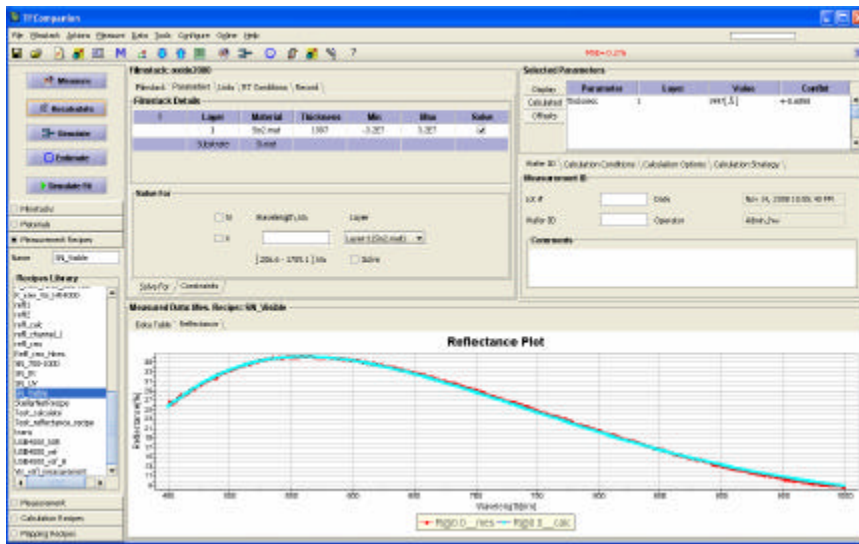


Fig. 1 Measurement of the thickness of 200nm oxide (SiO₂ 200nm/Si)

Optical measurements.

Optical thin-film measurements are indirect – they, actually, include two steps:

1. Measurement of reflectivity/transmittance spectrum of the sample
This step includes collecting the signal from spectrometer (raw data) and normalizing it using calibration data.
2. Analysis of measured data using optical model of the sample (filmstack).
Software compares measured and simulated data and infers the filmstack parameters (calculated thickness and/or optical properties) from the best fit (curve fitting).

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TFCCompanion software makes the measurement process smooth and transparent to the user.

A typical measurement includes only two steps:

- Select optical model (filmstack) corresponding the sample
- Click “Measure” and check calculation results*

*If it is a first measurement (in this session) user will be prompted to perform calibration before the measurement

TFCCompanion software encapsulates details of the measurement process in the *Measurement Recipe* to make it easy and transparent to the user.

There are three types of measurement recipes:

- ✓ **Measure ONLY** (no calculation). This type of the recipe performs only the first step (as described above) – measurement of the normalized reflectance or transmittance. The user can perform the calculation step manually using *Recalculate* button in the main screen. **Measure ONLY** recipes are typically used for either preliminary measurement on the new samples or to save/export the data for further analysis as later time.
- ✓ **Measure & Calculate (no filmstack attached)**. This is a *default* type of the recipe that performs two measurement steps automatically. For calculations it uses the current filmstack (filmstack that was set prior to measurement).
- ✓ **Measure & Calculate (filmstack attached)**. This type of the recipe performs two measurement steps automatically, similar to previous recipe type but it also allows specify the measurement filmstack. When measurement recipe is loaded – the filmstack attached to the recipe is loaded automatically (overrides current filmstack).

Tip. *The type of the recipe can be easily changed in Recipe Dialog (Measure/Review Recipes from the main menu)*

In most cases, user does not need to create a Measurement recipe explicitly – the default recipe is automatically created when Measure button in pressed.

The Default recipe uses spectrometer and measurement configuration information. The spectrometer information is either read from spectrometer or configuration file and can be edited by the user (see Fig. 2). Measurement configuration is defined in Software Configuration Dialog (Configure/Configure software) and can be modified by the user (see Fig. 3) as well.

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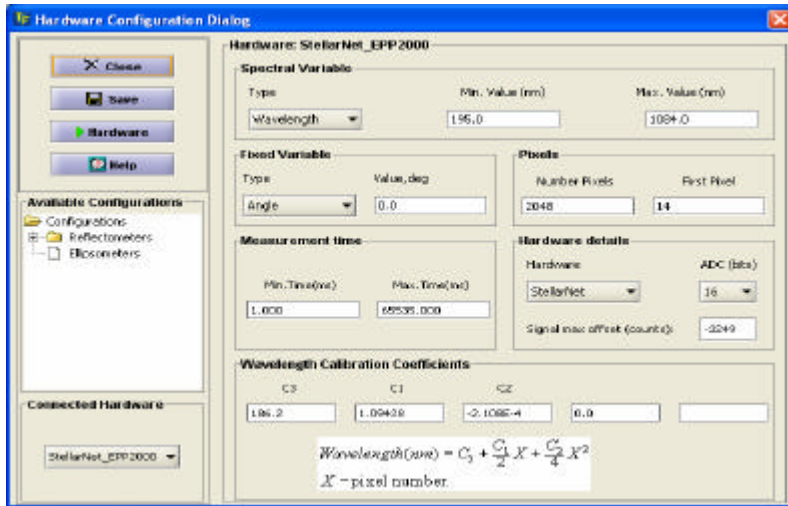


Fig. 2 Hardware configuration dialog. The data is typically read directly from spectrometer or configuration file. User can edit/modify the parameters.

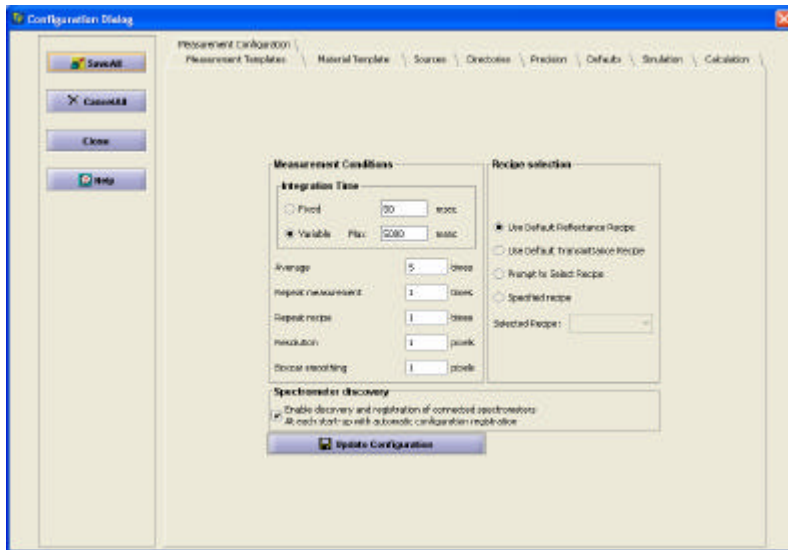


Fig 3 Measurement configuration. Defines default measurement conditions and recipe selection options (Configure/Configure Software and select Measurement Configuration tab).

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Calibration.

The raw intensity signal acquired from spectrometer is a convolution of sample's reflectivity/transmittance and several other factors: spectral radiation of the light source, transmittance of the optics, spectral sensitivity of the detector, etc. Calibration is required to extract actual reflectivity/transmittance of the sample from the raw signal.

Calibration is performed in a two steps process:

1. Measurement of the reference sample.
In case of transmittance calibration – the transmittance of the air (no sample) is used (100% transmittance)
In case of reflectance calibration – a bare Si reference sample is used (It is possible to use other reference samples, with well known and stable reflectivity, as well)
2. Measurement of the dark current signal.
Measurement of the signal with illumination blocked.
Note. *For reflectance calibration it is recommended to use an absorbing black sample (provided with instrument). This method works both in the case of a standard reflectance probe and reflectance probe with attached lens. Blocking the light source (e.g. with shutter) will work only in the case of the standard probe since it does not account for the back reflectance from the lens.*

A Calibration recipe (a special type of the measurement recipe) manages calibration. In almost all cases, it is **NOT necessary** to create a calibration recipe manually – it is created automatically.

User is prompted to performed calibration before the first measurement (to force recalibration – select *Measure/Clear Calibration* from the main menu). Calibration recipe is created automatically, on a fly, to match current measurement recipe.

Note. *There are two special cases when calibration recipe needs to be created explicitly:*

- ✓ *Non standard reference sample used for reflectance calibration (standard sample is Si)*
- ✓ *Two separate calibration recipes are used: one for reference sample, another for dark current measurement. (this is typically used when software is controlled by the external program)*

The result of calibration is the mapping between known reflectivity and the raw signal intensity (in units of ADC counts)– an example of calibration result is shown on Fig. 4

Tip. *To review current calibration, select *Measure/Review Calibration (Reflectance)* or *Measure/Review Calibration (Transmittance)**

The best way to check the calibration is to measure the reference sample (used in calibration) or empty space in case of Transmittance. Known reflectivity of reference sample and measured data should match (Fig. 5). If there is a shift or discrepancy between the data – one needs to recalibrate.

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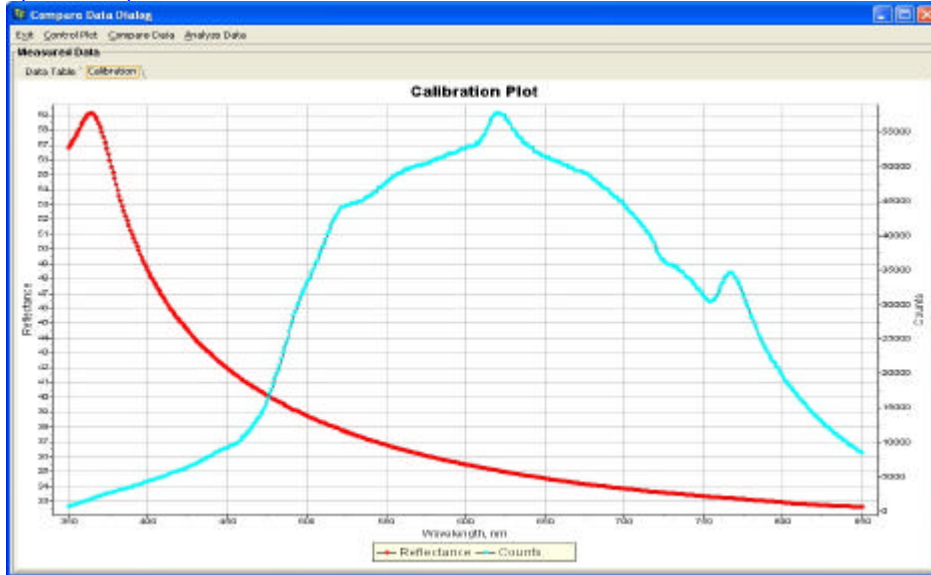


Fig. 4 Results of reflectance calibration. Red line – known reflectivity of the Si wafer LHS axis, blue line – raw signal from spectrometer RHS axis (ADC counts)

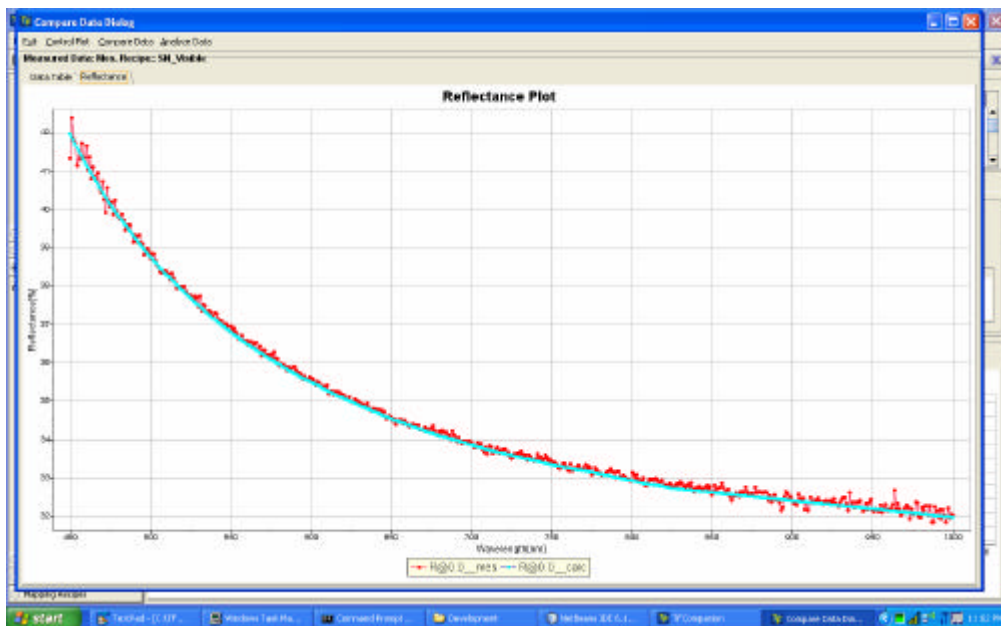


Fig. 5 Calibration test – measurement of Si reference sample. The blue line is the theoretical (simulated) reflectance of the reference sample; the red line is measured reflectance. A good match verifies that calibration was done well.

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Practical measurement procedure.

The measurement workflow is presented on Fig. 6.

1. Select Measure button
2. If no measurement recipe is found – the option defined in Measurement configuration is used
3. Calibration is checked: if there is no calibration or calibration is not consistent with the measurement – user is prompted to calibrate (calibration recipe is created automatically to match current measurement recipe)
4. Measurement is taken
5. If measurement recipe includes calculation – the calculation is performed and results displayed.
6. If calculation is not included – normalized reflectivity or transmittance spectrum is displayed. User can do calculation manually using Recalculate button.

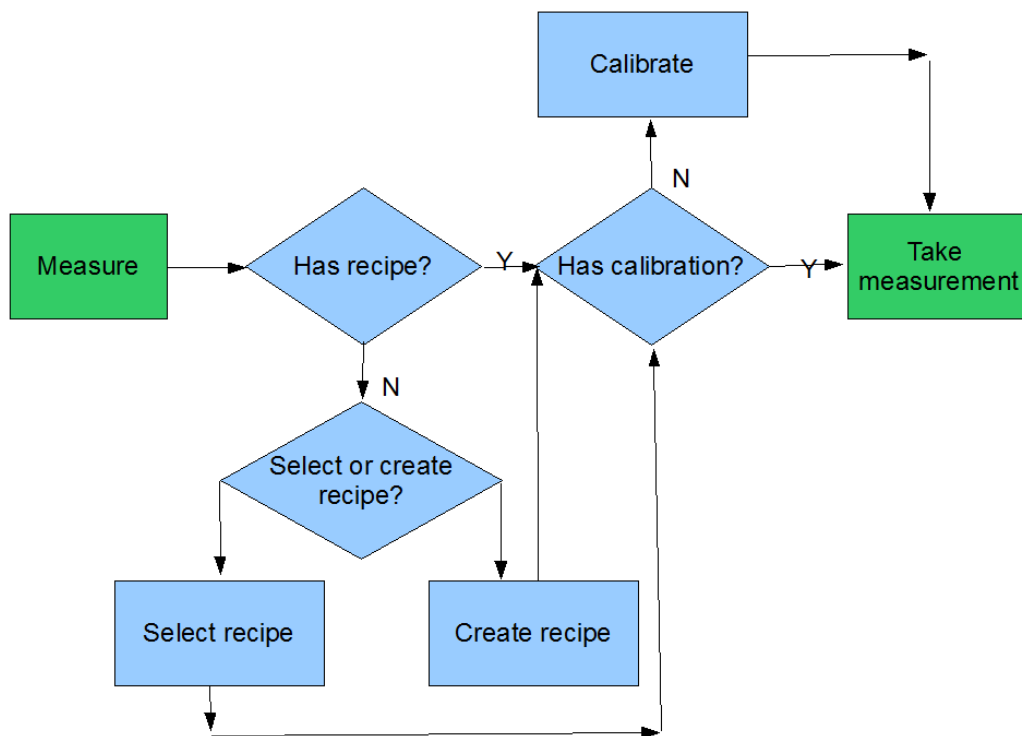


Fig. 6 Workflow of the measurement process.

Salient points:

- ✓ *No need to prepare measurement recipe before the start of measurement, in most cases*
- ✓ *Calibration recipe is created automatically*

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Inside measurement Recipe.

Each measurement recipe has several components:

- ✓ Spectrum (Spectrum definition and Measurement conditions)
- ✓ Attributes (recipe type, target hardware, etc)

Spectrum definition includes:

- ✓ Spectral range: it should be within the range of the currently connected spectrometer. (Spectrometer does not have to be physically connected but selected in Hardware Configuration dialog)
- ✓ Number of points/steps
- ✓ Measured parameter: Reflectance or Transmittance

Measurement Conditions:

- ✓ Channel: the spectrometer channel as defined by spectrometer driver
- ✓ Integration time: fixed or variable
- ✓ Average – defines the number of signal averages performed in spectrometer driver
- ✓ Repeat measurement – has the same averaging effect (as Average above) but it also calculates actual standard deviation and add it to the measured data
- ✓ Repeat recipe – similar to Repeat measurement but, in case of variable integration time, time is adjusted for each measurement.
- ✓ Resolution – number of pixels read independently, e.g. 2 mean that each 2 pixels will be averaged
- ✓ Boxcar smoothing – signal smoothing performed by spectrometer driver

Integration time: fixed or variable?

Variable integration time (default) allows software to adjust time to achieve ~ 80-90% of the maximum signal (ADC range). Measurement of different samples or different point on the sample can be done using best signal/noise.

Note. Integration time is adjusted down to 1ms (minimum step is 1 ms) If the light intensity too strong and 3-4 ms give maximum signal – software may not be able to adjust the time correctly.

Fixed integration does not allow any adjustment independent of the signal strength i.e. saturation or low signal are not checked.

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Calculation

Calculation is a process of inferring physical properties of the sample i.e. thickness and/or optical properties based on measured reflectance and/or transmittance. Nonlinear minimization/curve fitting requires that the starting/nominal values of the parameters be relatively close to actual values. For thickness, the difference between starting and measured value is typically <500Å (for oxides). If the starting value is too far away – calculation may not converge and will be “trapped” in local minimum.

In some cases, the thickness of the layer is not known a priori and/or can vary in a wide range.

There are two methods that help solving this problem:

- ✓ The grid search (global search)
- ✓ Power Spectrum Density/ FFT analysis

Grid Search

The grid search defines a grid of starting thickness values to check – the calculation is done all the values and the best-fit result presented as a solution. For example, if the layer can be in 1000Å-10000 Å and 19 point grid is selected- calculation will be performed for thicknesses 1000 Å, 1500 Å, 2000 Å, etc. and the best result will be selected. The grid search is working well but has a problem – for a wide range of thicknesses calculation can be time consuming.

FFT analysis

FFT method can be applied only to thick dielectric or lightly absorbing films. It is based of the analysis of the oscillation pattern (constructive/deconstructive interference) of the spectrum. This method requires that the measured spectral range include fair amount of oscillation periods. In the visible range - this typically applicable for layers more than 3um thick.

FFT analysis can be used as an independent method for determining thickness (this is a preferred method for more thick films >10um) or used in combination with the curve fitting.

Grid Search can be defined for specific layer(s) of the optical model (filmstack) and is a part of the filmstack.

The type of the calculation: Fit (Marquardt-Levenberg), FFT, FFT+Fit can be defined in the main screen or in Software configuration dialog.

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There are several more advanced calculation options that can be used:

- ✓ Multiple try calculation strategy (defined several models and trigger fit level) – this allows to speed up calculation of complex filmstacks
- ✓ Linked layers/materials allows reduction of the number of calculated parameters in cases of multilayer filmstacks with repeated layers (e.g. some anti-reflection coating and heterostructures)
- ✓ Signal scaling – allows to correct intensity/ambient light variation in long running in-situ measurements.
- ✓ Multiple samples data analysis. Simultaneously analyze data from several samples. For example, one can use several similar samples with different thickness of one layer to improve the quality of the optical constants calculation (of the specific material)
- ✓ Batch processing of the data. Allows offline analysis of a series of measurements e.g. online measurements, etc.

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Optimizing measurement precision.

Variable integration time (default) in the measurement recipe allows to utilize maximum dynamic range of the electronics (ADC) by adjusting the signal to the 90-95% of the maximum signal.

To adjust integration time properly software needs to know “the real”/experimental maximum signal – this is the signal corresponding to a saturation level. The default maximum signal is defined by the ADC bits e.g. 16 bits correspond to 65536 counts, 14 bits -> 16384 counts. The saturation level signal can differ from the “theoretical” value e.g. 16 bits ADC signal may have from 62000 to 66000 (for different system) instead of 65536 counts. This offset needs to be corrected.

1. Set reflective sample e.g. Si sample
2. Start signal monitor (Measure/Signal monitor) from the main menu
3. Select Properties/Measurements Condition from the Monitor window menu and adjust integration time to saturate the signal (flat top)
4. Select Correct/Saturation Offset from the main menu. The dialog (Fig. 4) will appear
5. Select Set Offset – current spectrometer configuration will be updated

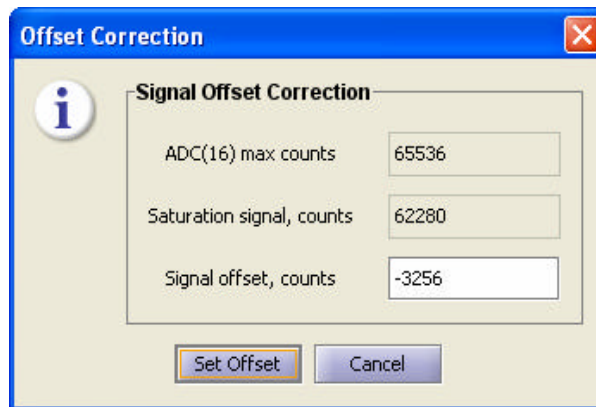


Fig. 7 Offset correction. This dialog shows the real maximum signal (saturation level) and calculates the offset (in this case: -3256) that needs to be applied

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Measurement Examples.

In the beginning of this document we discussed that data acquisition and modeling are two separate steps of the measurement process. Depending on selected type of the measurement recipe they can be performed either automatically together or separately. For new/unknown or complex samples, it is better to collect the data (Measure Only recipe type) and develop the model and analyze results offline. Once the model is developed, one can use the “Measure & Calculate” type recipe for future measurements

1. Measurement of oxide (Thickness measurement)

This is basic measurement: we selected oxide2000 filmstack, selected thickness as a calculated parameter and use the default: “Measure and Calculate” type recipe. Results of the measurement and fit are presented on fig. 1 (beginning of the document)

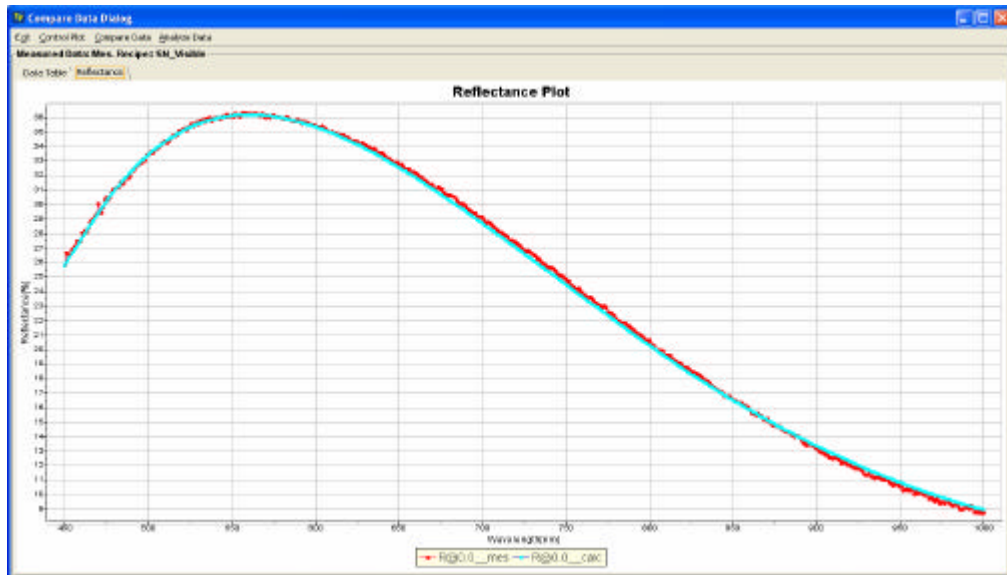


Fig. 8 Full screen zoomed results of the Fig. 1. Shows a good fit between measured and calculated data.

2. Dynamic measurement

In process monitoring applications (inline, in-situ) one needs continuous measurements. A dynamic measurement plugin option enables this functionality and allows selecting different measurement and calculation strategies. In this example we will select 100 sequential measurements to check repeatability. The measurements are done on the same 2000A oxide sample (as above) using the same measurement recipe.

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To select Dynamic measurement we use: **Actions/Dynamic Measurement** from the main menu, select filmstack, measurement recipe and measurement strategy in the displayed dialog and start the measurement.

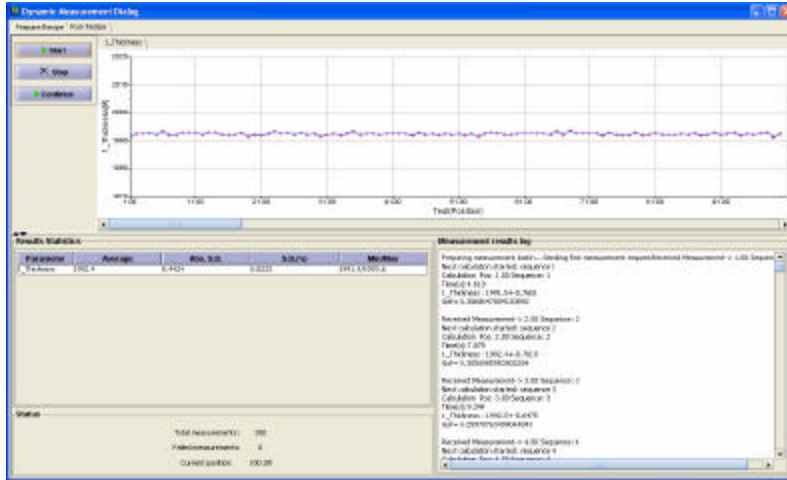


Fig. 9 Results of dynamic measurement.

Trend chart shows results of every measurement and statistics table shows ~ 0.4A standard deviation.

Results of the measurement are displayed on a trend chart(s), statistics table shows s.d., min/max and average for each calculated parameter and are continuously updated. Measurement report and/or individual measurement can be saved to file(s).

3. Thickness and n, k measurement (nitride example).

Spectral reflectance/transmittance measures optical thickness – $n \cdot T$, where n is reflective index and T is physical thickness of the layer. For dielectric materials (non-absorbing i.e. $k=0$) it is impossible to measure n & T independently (they are strongly correlated). This means that one need to know optical dispersion of the material in order to determine the thickness. If material is absorbing ($k>0$) it is possible to decouple n & T and independently measure T , n , k by representing optical dispersion using parameterized approximation: Tauc-Lorentz or Oscillator, etc.

Following example shows results of 700A nitride measurement in 200-1000nm range.

The data was analyzed using two different approaches:

1. Use standard Si₃N₄ material data and calculate only thickness.(only T case).
Measured thickness: 725A
2. Represent nitride dispersion using Tauc-Lorentz approximation and determine T, n, k simultaneously (T,n,k case). Measured thickness: 738A

Only T case, gives good fit in the visible range (Fig. 9) where nitride is dielectric ($k=0$) and T,n cannot be determine independently anyway. But UV part shows discrepancy that indicate that use optical properties are not accurate (at least in UV range)

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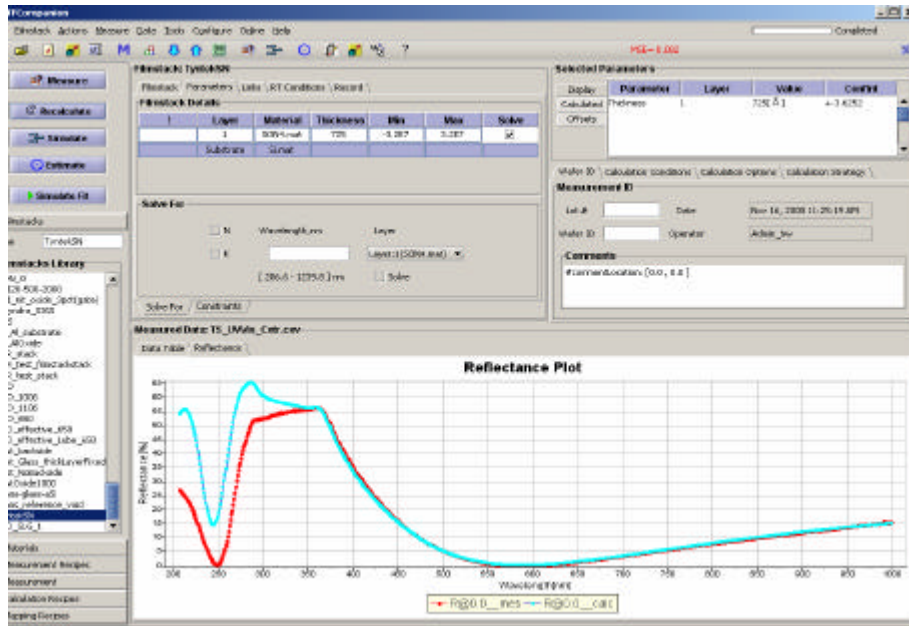


Fig. 10 Fit of measured and calculated data for 700A nitride. Using standard nitride optical constants (only T case). UV part show some discrepancy but visible spectrum has a good fit.

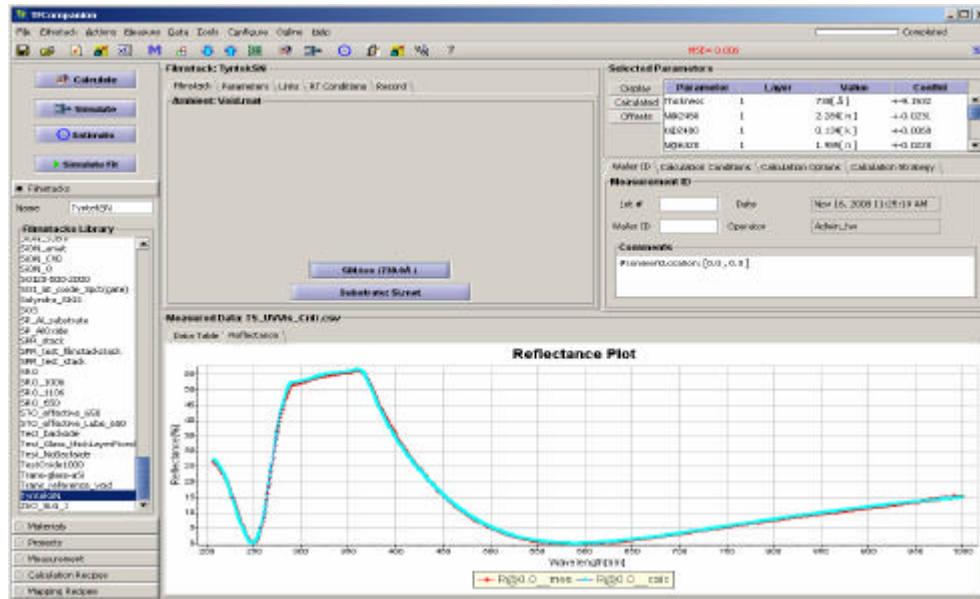


Fig. 11 Fit of measured and calculated data for 700A nitride (T,n,k measurement). Nitride optical dispersion is represented using Tauc-Lorentz approximation (see Fig. 12 for nitride dispersion)

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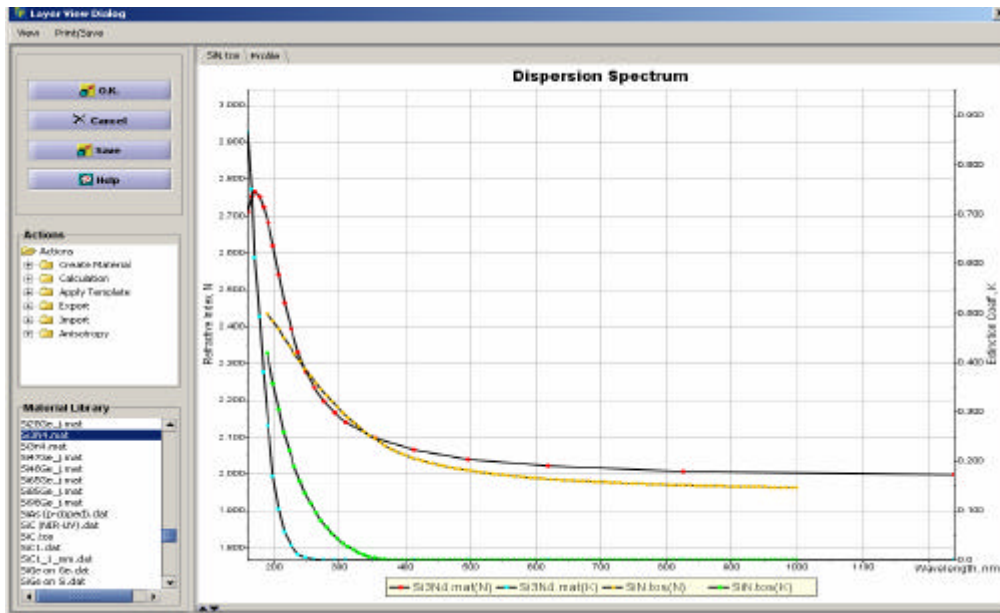


Fig. 12 Comparison of the standard nitride optical dispersion and measured dispersion (represented with TL approximation).

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4. Thick polymers measurement.

Measurement of the very thick films presents unique challenges. The standard curve fitting is becoming difficult because:

a). The optical phase cycle is $< 200\text{nm}$ for most polymers. This means that fitting algorithm has difficulty adjusting outside this range (“trapped in local minimum”). Global grid search can be used to examine wider range of thicknesses but it make calculation very slow. 200nm is a small value compared with the thickness of the polymer ($\sim 100\mu\text{m}$).

b). Optical properties of the polymers are not accurately known. For example there maybe small absorption but because of the large thickness of the layer the effect is significant.

The better approach is to use Thick film algorithm that is based on Fourier analysis of the measured data.

Example 1: Free standing thick polymer film

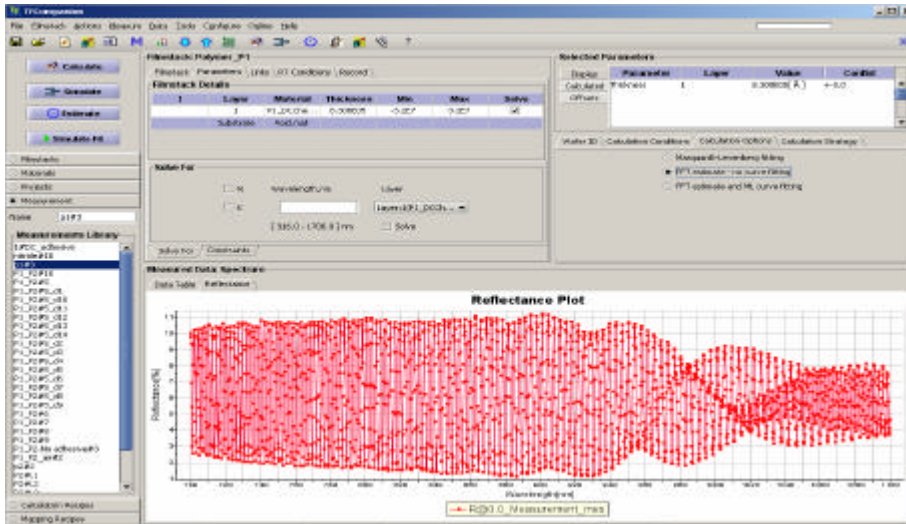


Fig. 13 Reflectance measurement of the freestanding polymer ($\sim 80\mu\text{m}$).
Spectrometer range: 700-1100nm, resolution: 0.2nm

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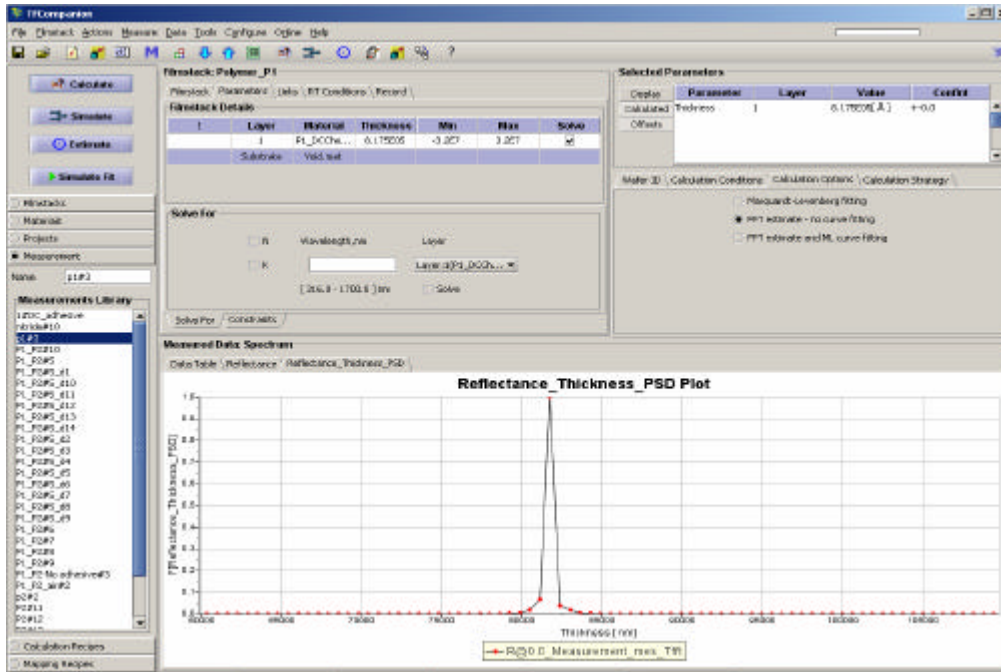


Fig. 14. Results of using thick-film algorithm (FFT) to analyze measured reflectance data for free standing polymer (Fig. 13). Peak indicates thickness of 81.3um

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Example 2. Free standing Polymer with adhesive layer

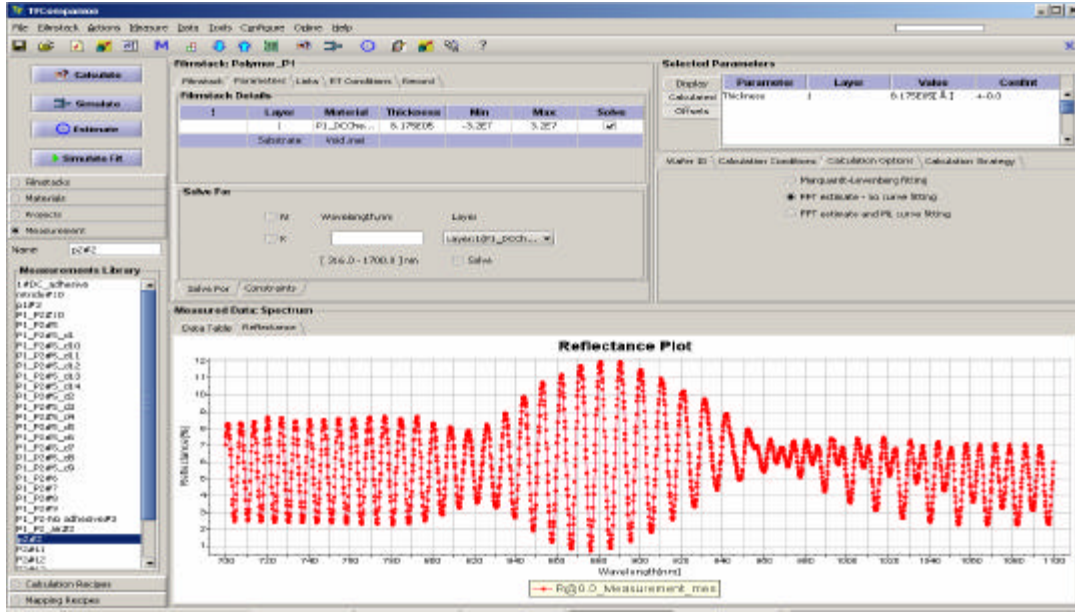


Fig. 15 Reflectance measurement of the polymer (~ 26um) with a thin adhesive layer (~ 1um)

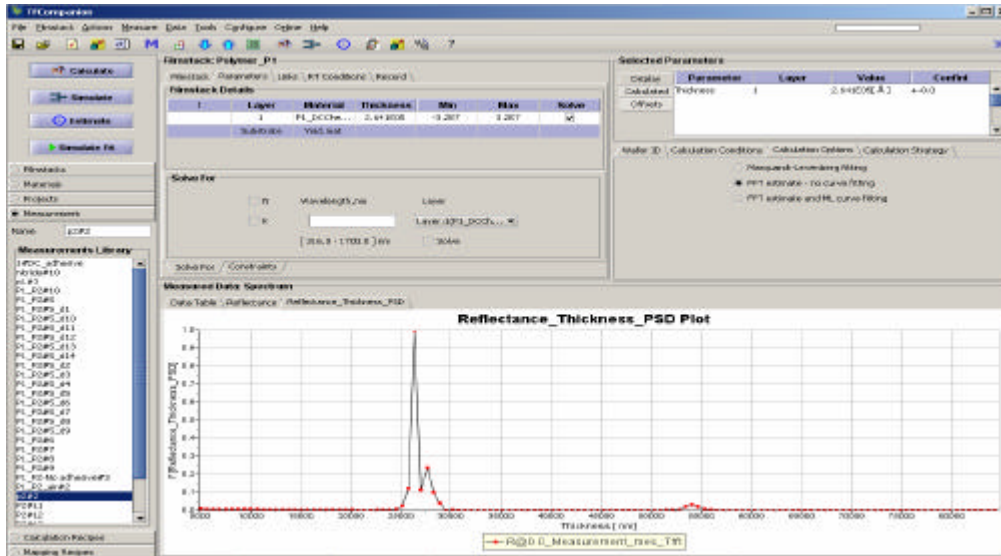


Fig. 16. Polymer measurement – thickness calculation results. Two peaks indicate that there are two layers: 26.41μm and ~1.26μm (peaks positions: 26.41 and 27.67)