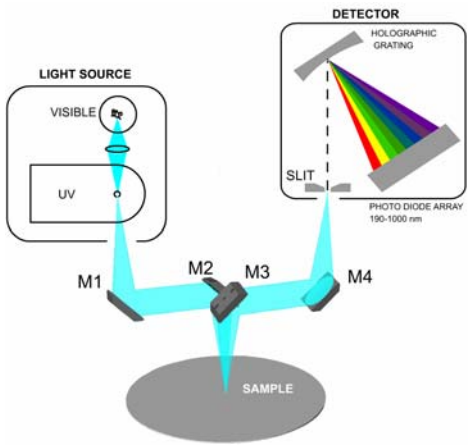
Optical Measurement of Thickness and Properties of Ultra-Thin Films in Complex Multi-Layer Film Stacks Used in MRAM Fabrication



Alexander Gray, Jacob McPherson
n&k Technology, Inc., Santa Clara, CA

May 18th, 2005

Introduction

All semiconductor manufacturers require an accurate reliable metrology technique for the measurement of thickness and optical properties of thin films used in the fabrication process.

The MRAM industry is no exception to this rule. In addition, the narrow range of acceptable film conditions coupled with the complicated, multi-layer film stack of MRAM devices, requires the use of an ultra-high resolution metrology solution capable of detecting sub angstrom changes in thickness for each layer of a multiple layer MRAM film stack.

Metrology Challenges:

1. **Complexity of the multi-layer film stacks used in MRAM fabrication.**
2. **Characterization of multiple metallic films in the MRAM film stack.**
3. **Need for ultra-high (sub-Angstrom) resolution for the thickness measurement.**

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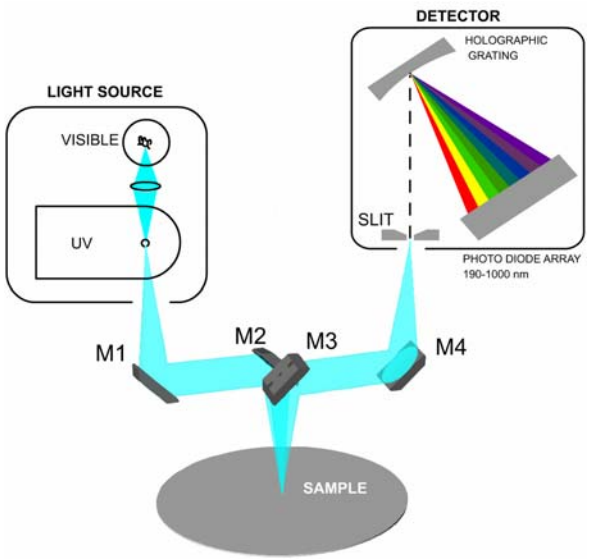
Methodology
Hardware

- ***Method: Broadband Reflectometry***
- ***Spectral Range: 190 nm – 1000 nm***
- ***Optical Design: All-Reflective Optics***



n&k Analyzer 3300

Methodology
Analysis Model

Forouhi–Bloomer Dispersion Relations:

$$k(E) = \sum_{i=1}^{q} \frac{A_i (E - E_g)^2}{E^2 - B_i E + C_i}$$

$$n(E) = n(\infty) + \sum_{i}^{q} \frac{B_{0_i} E + C_{0_i}}{E^2 - B_i E + C_i}$$

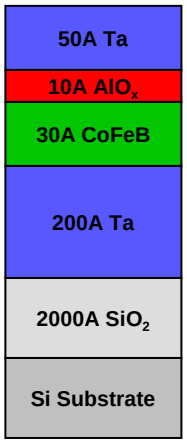
The "n&k Method" is an accurate, reproducible thin film characterization technique, that incorporates the Forouhi-Bloomer dispersion relations for $n(\lambda)$ and $k(\lambda)$ into Fresnel equations to generate theoretical Reflectance spectrum (R_{theor}) in terms of d, $n_f(\lambda)$, $k_f(\lambda)$, E_g, $n_s(\lambda)$, $k_s(\lambda)$, $\sigma_1(top)$ and $\sigma_2(bottom)$, whereby the wavelength and material dependence of $n(\lambda)$ and $k(\lambda)$ are obtained from the Forouhi-Bloomer formulation.

Analysis Method

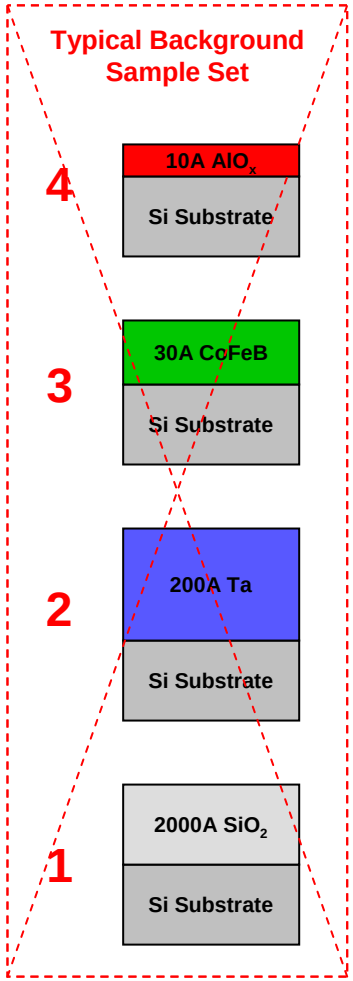
Choice of Appropriate Background Sample Set

Film Structure

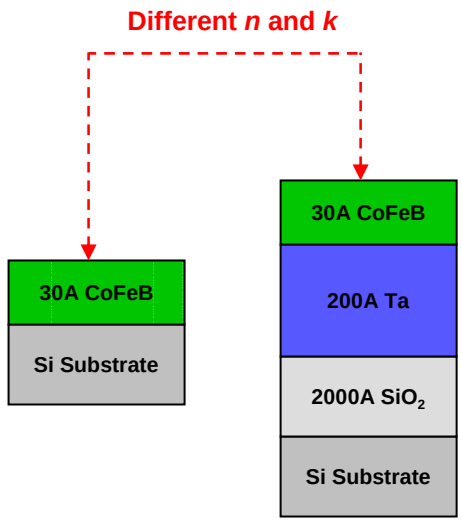
Challenge: Measure optical properties (n and k) and thickness of all layers in the following film structure:



Problem: *n* and *k* of each individual layer has to be determined. A set of background samples is necessary for this task.



PROBLEM !



Therefore, single-layer background samples cannot be used to characterize the optical properties (*n* and *k*) of materials

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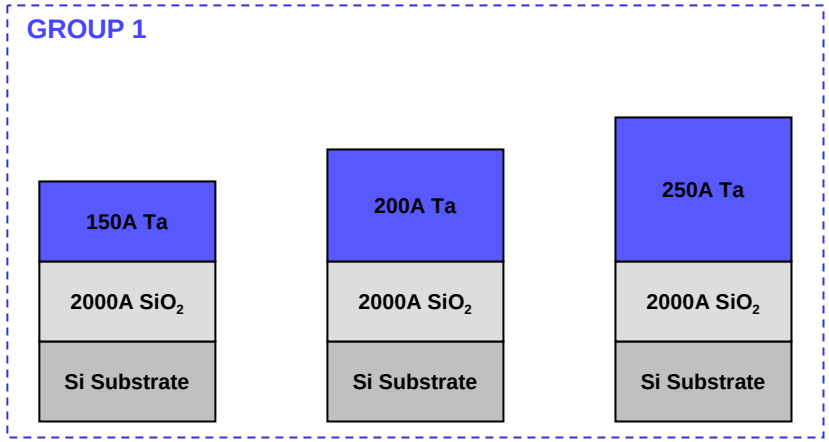
Background Samples

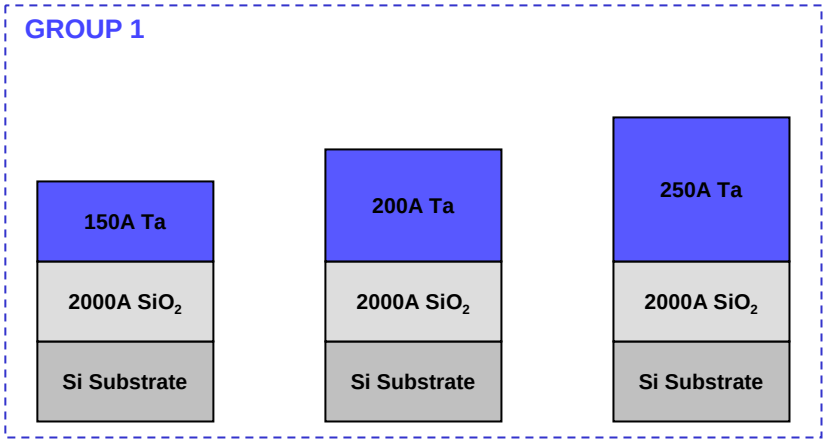
Sample Group 1: Used for Characterization of Ta

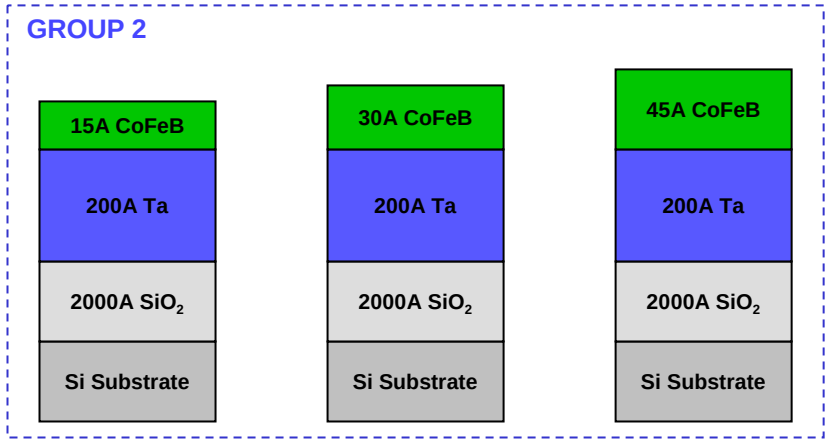


Three samples were produced for the purpose of characterization of Tantalum.

Background Samples

Sample Group 2: Used for Characterization of CoFeB



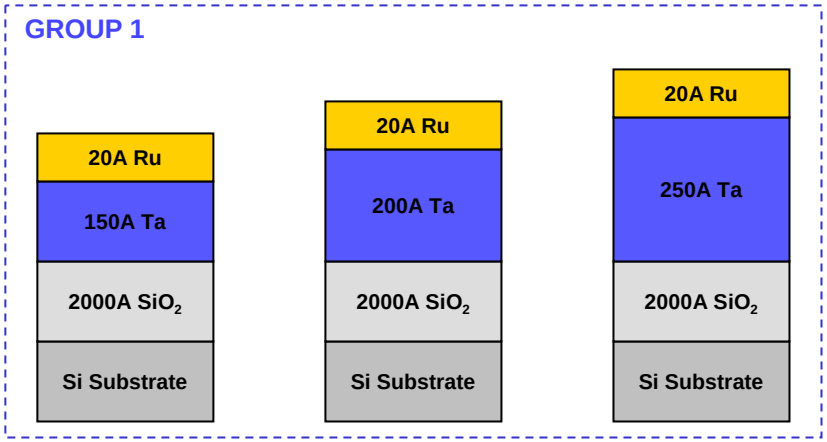


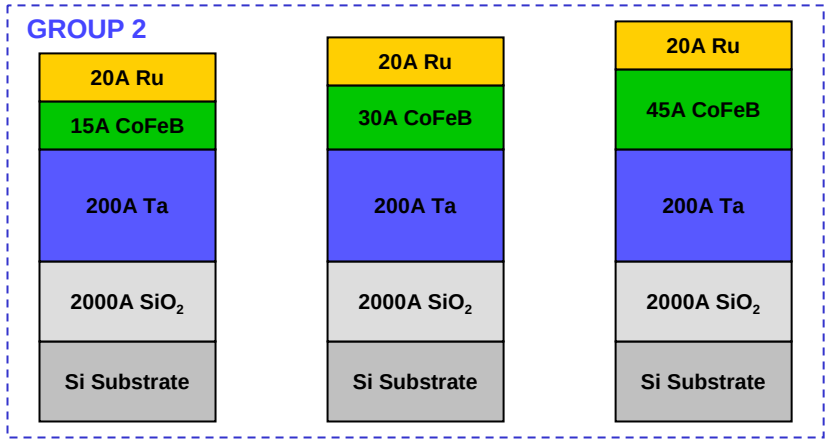
Three samples were produced for the purpose of characterization of Tantalum.

Another three samples were produced for the purpose of characterization of CoFeB.

Background Samples

Ru Buffer Layer





Three samples were produced for the purpose of characterization of **Tantalum**.

Another three samples were produced for the purpose of characterization of **CoFeB**.

In order to protect metallic **Tantalum** and **CoFeB** layers from natural oxidation, an ultra-thin layer of **Ruthenium** was deposited as a protective cap…

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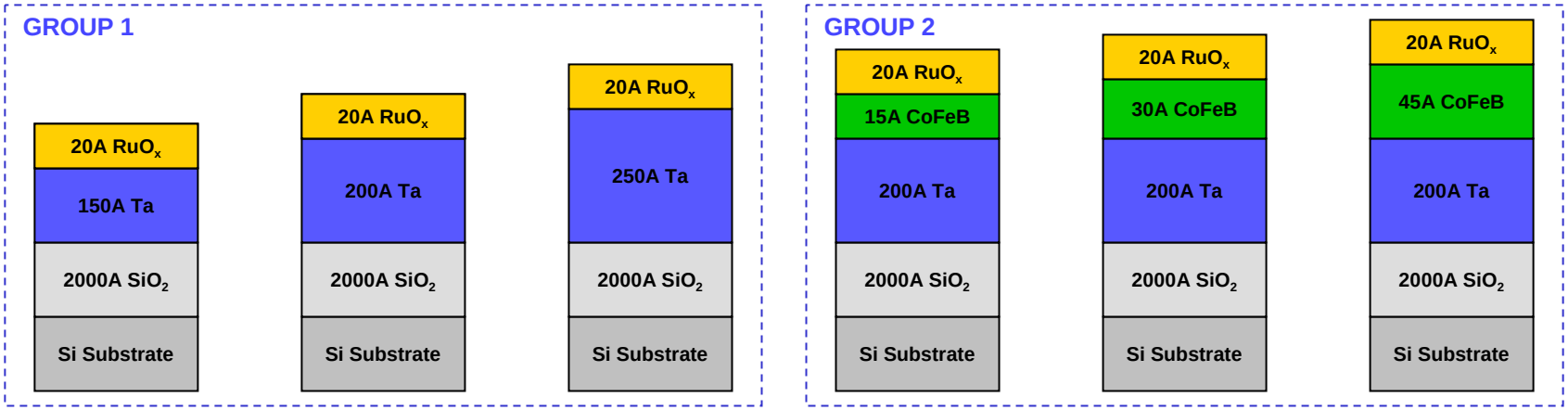
Background Samples

RuO_x Buffer Layer



Three samples were produced for the purpose of characterization of **Tantalum**.

Another three samples were produced for the purpose of characterization of **CoFeB**.

In order to protect metallic **Tantalum** and **CoFeB** layers from natural oxidation, an ultra-thin layer of **Ruthenium** was deposited as a protective cap…

… which eventually **oxidized** as the result of exposure to air.

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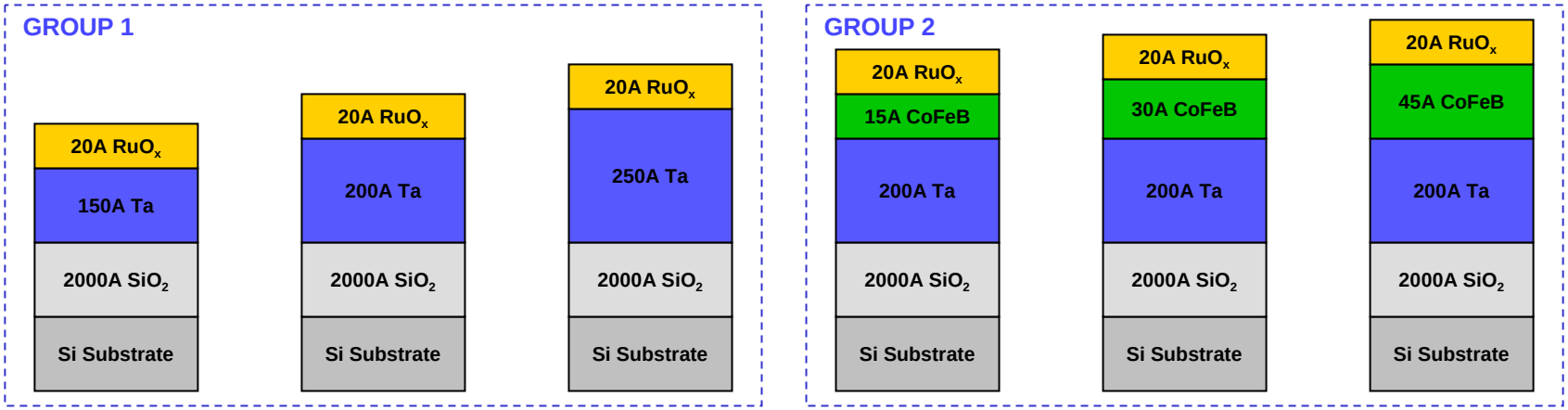
Thin Film Characterization

Simultaneous Analysis of Six Reflectance Spectra



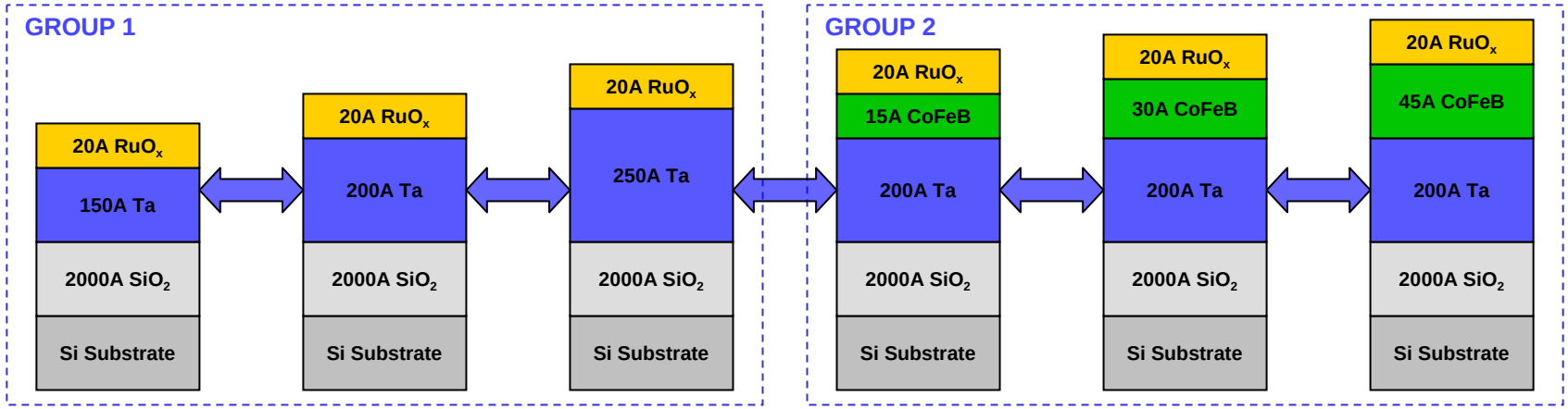
All six samples were analyzed simultaneously, using a patented multiple-spectrum analysis method*.

*United States Patent No. 6,091,485

n&k Technology, Inc.

Thin Film Characterization

Coupling of Optical Properties (*n* and *k*): Ta



All six samples were analyzed **simultaneously**, using a patented multiple-spectrum analysis method*.

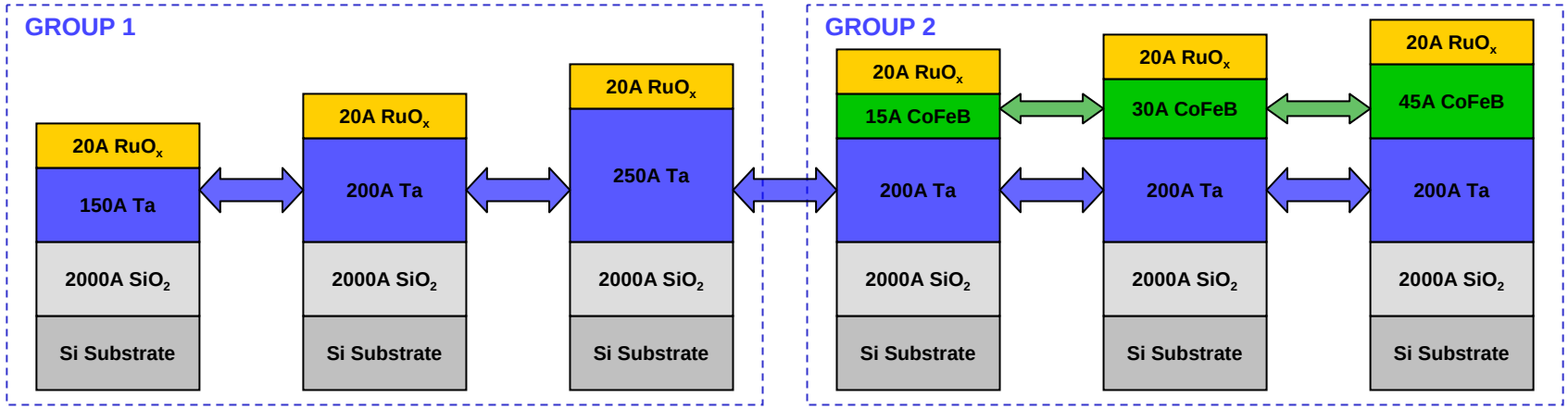
Optical properties (n and k) of **Ta** layers present in all six samples were **coupled** in the analysis recipe.

*United States Patent No. 6,091,485

n&k Technology, Inc.

Thin Film Characterization

Coupling of Optical Properties (*n* and *k*): CoFeB



All six samples were analyzed **simultaneously**, using a patented multiple-spectrum analysis method*.

Optical properties (n and k) of **Ta** layers present in all six samples were **coupled** in the analysis recipe.

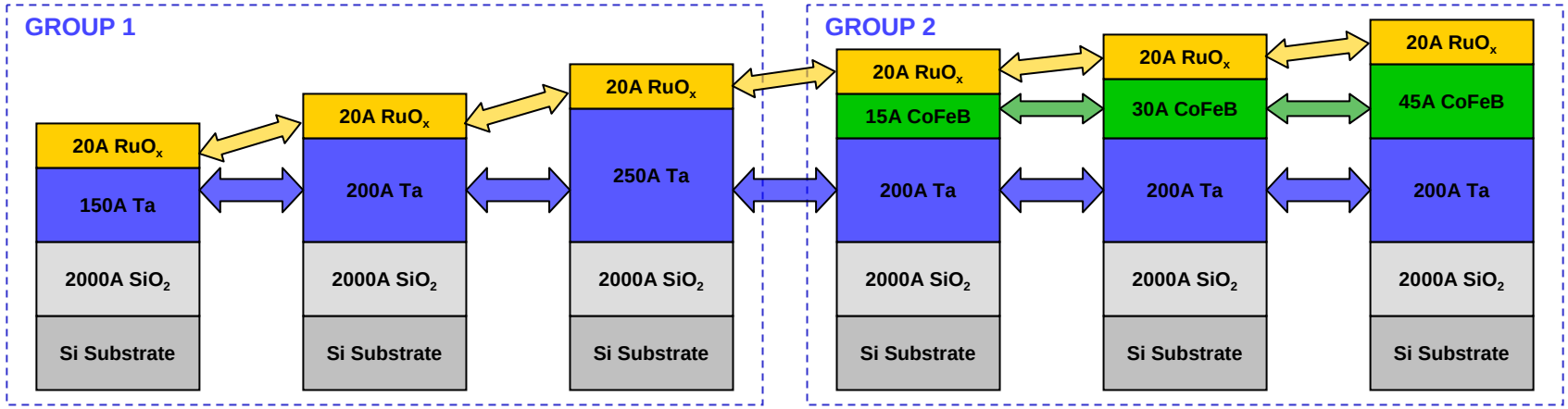
Optical properties (n and k) of **CoFeB** layers present in all six samples were **coupled** in the analysis recipe.

*United States Patent No. 6,091,485

n&k Technology, Inc.

Thin Film Characterization

Coupling of Optical Properties (*n* and *k*): RuO_x



All six samples were analyzed **simultaneously**, using a patented multiple-spectrum analysis method*.

Optical properties (n and k) of **Ta** layers present in all six samples were **coupled** in the analysis recipe.

Optical properties (n and k) of **CoFeB** layers present in all six samples were **coupled** in the analysis recipe.

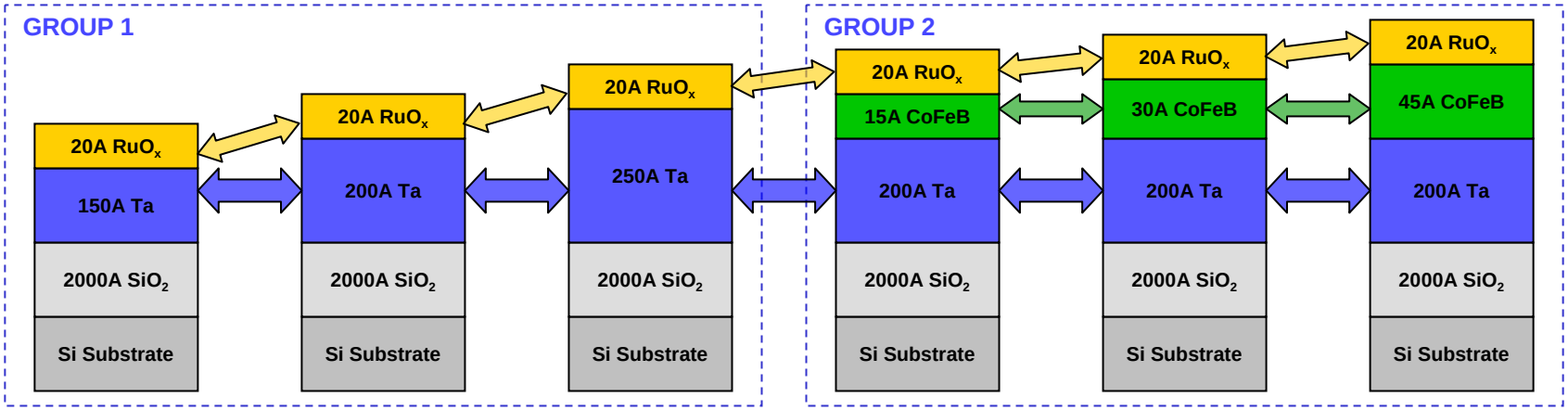
Optical properties (n and k) of **RuO_x** layers present in all six samples were **coupled** in the analysis recipe.

*United States Patent No. 6,091,485

n&k Technology, Inc.

Thin Film Characterization

Simultaneous Analysis of Six Reflectance Spectra



All six samples were analyzed **simultaneously**, using a patented multiple-spectrum analysis method*.

Optical properties (n and k) of **Ta** layers present in all six samples were **coupled** in the analysis recipe.

Optical properties (n and k) of **CoFeB** layers present in all six samples were **coupled** in the analysis recipe.

Optical properties (n and k) of **RuO_x** layers present in all six samples were **coupled** in the analysis recipe.

Six unique Reflectance spectra (190 – 1000 nm) were analyzed simultaneously, to obtain thicknesses, *n* and *k* of all layers.

*United States Patent No. 6,091,485

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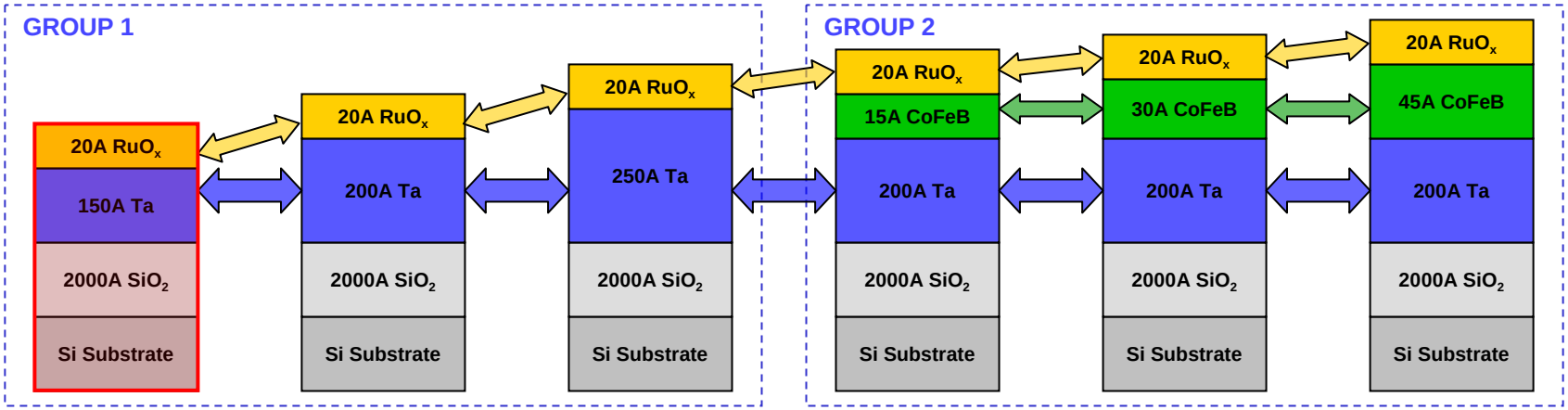
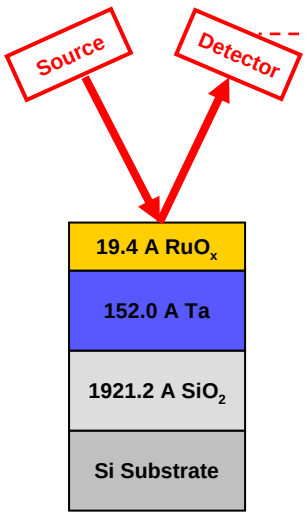
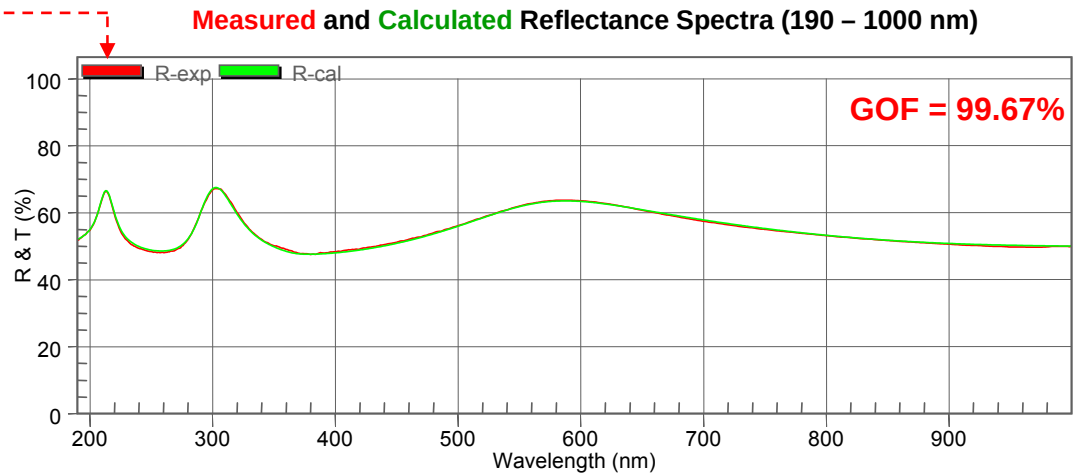
Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 1

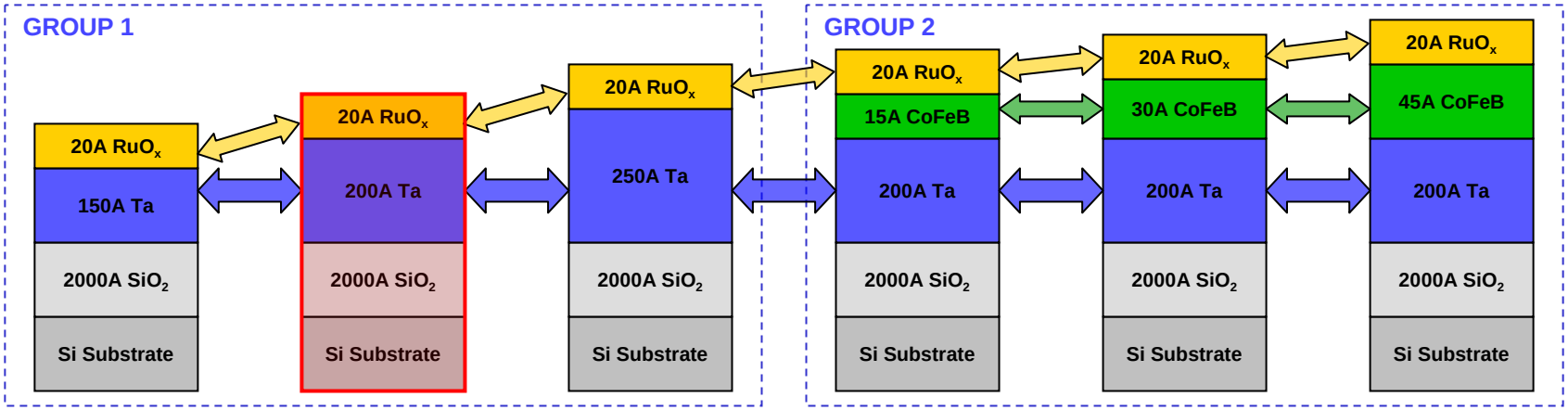


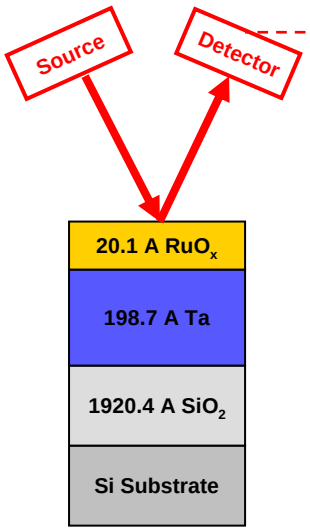


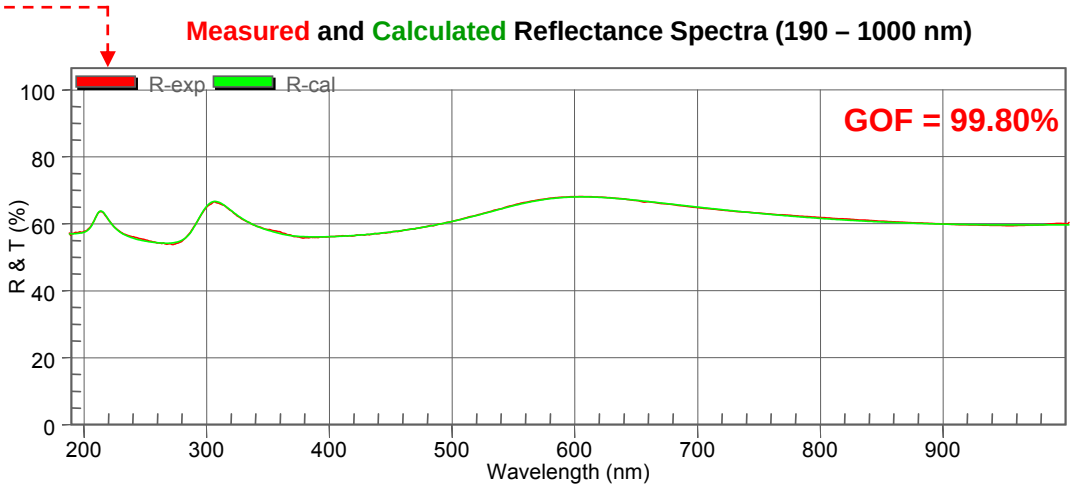


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 2

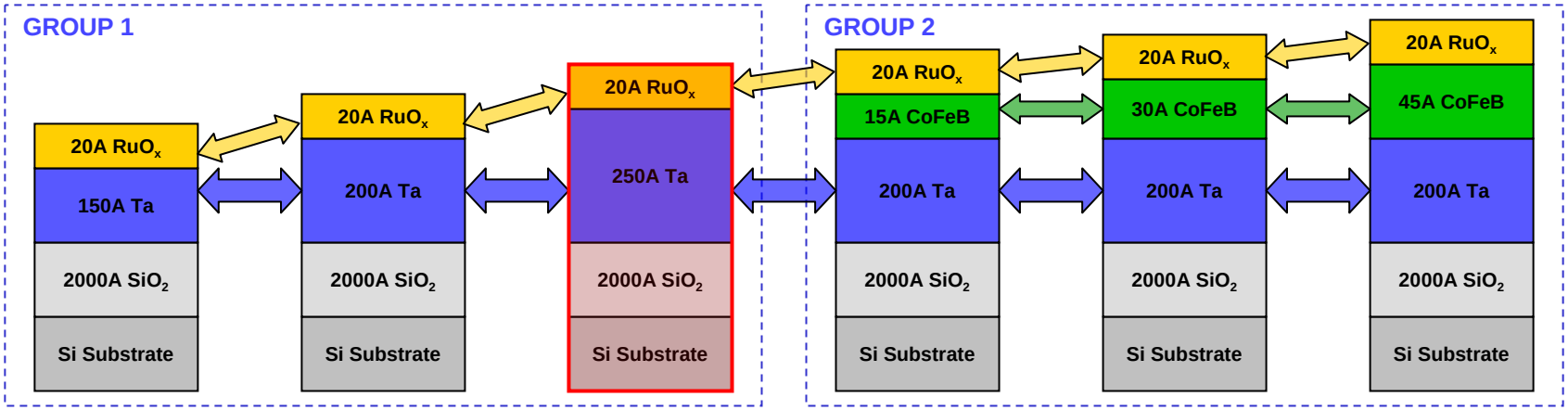


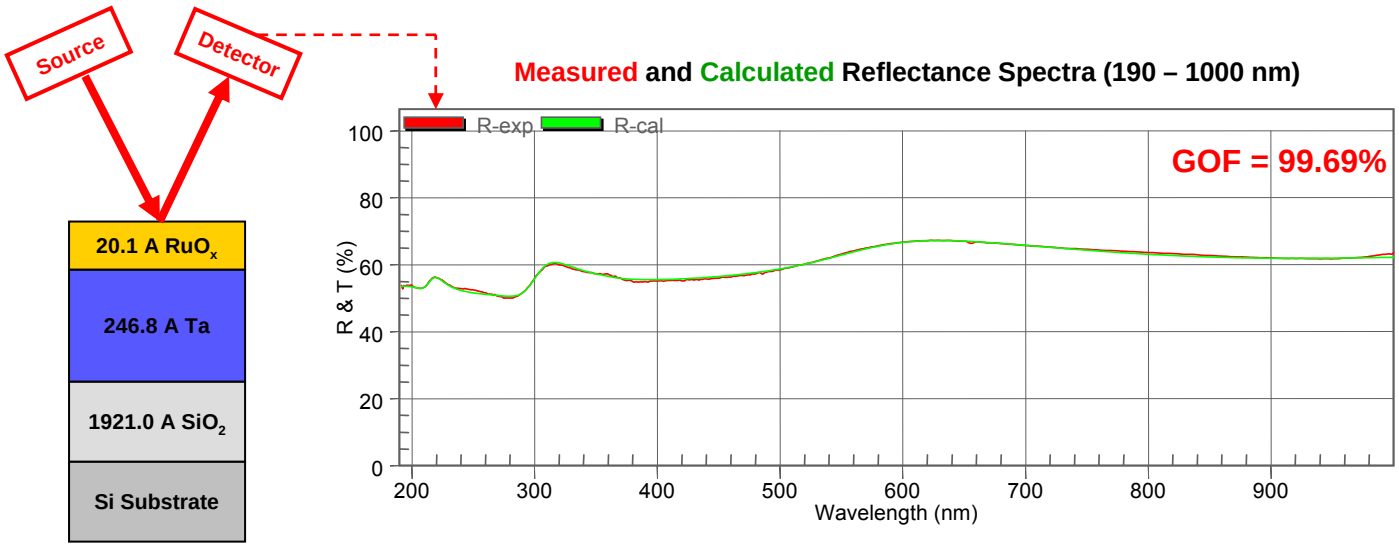




Analysis of Reflectance Spectra

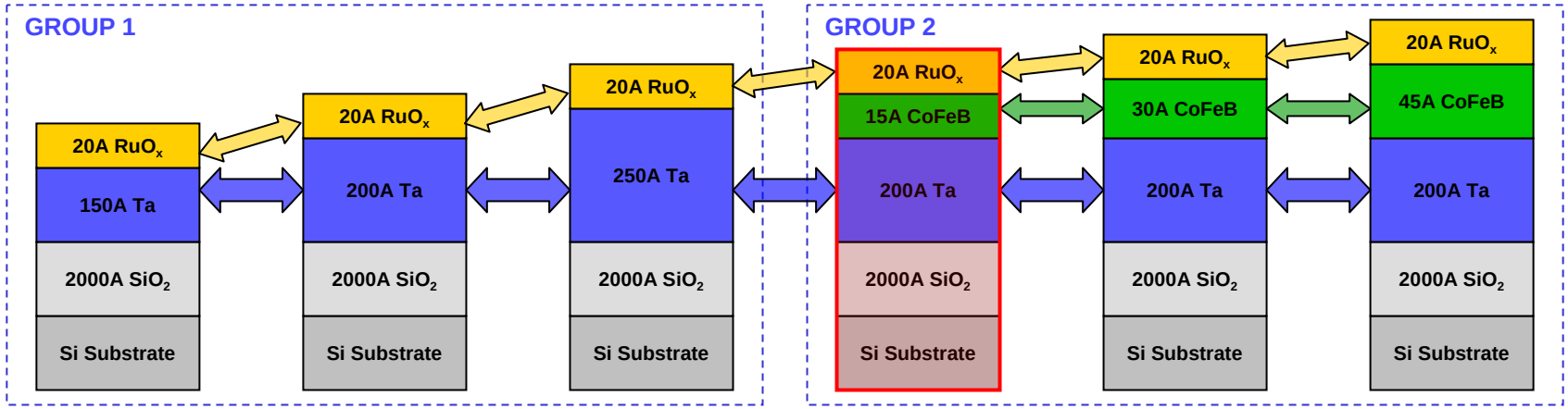
Simultaneous Analysis of all 6 Samples: Sample 3

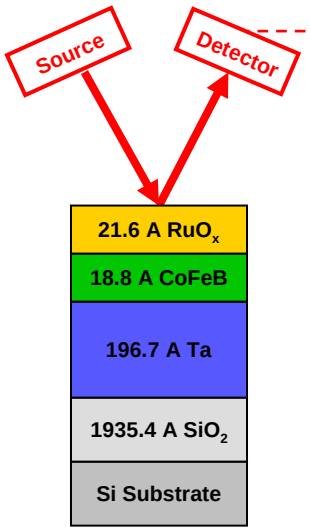


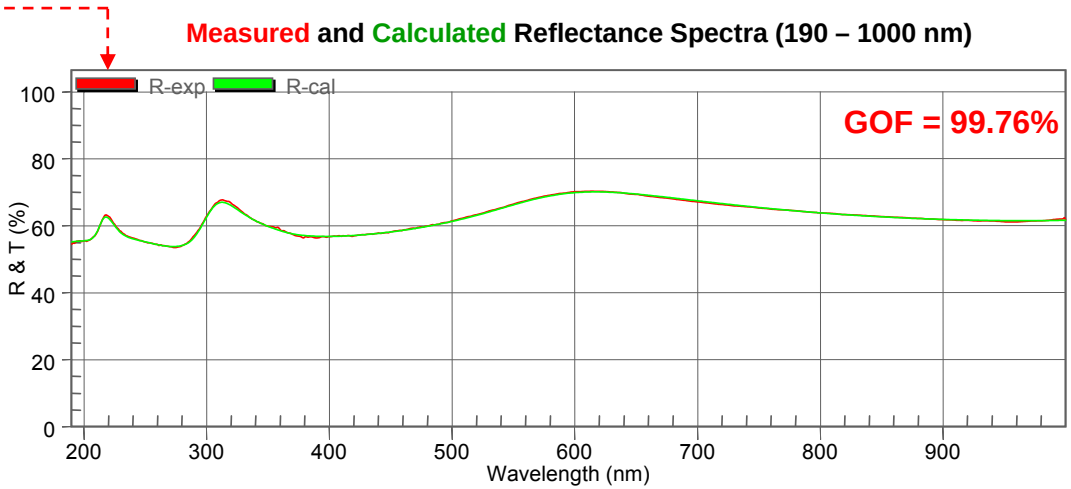


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 4

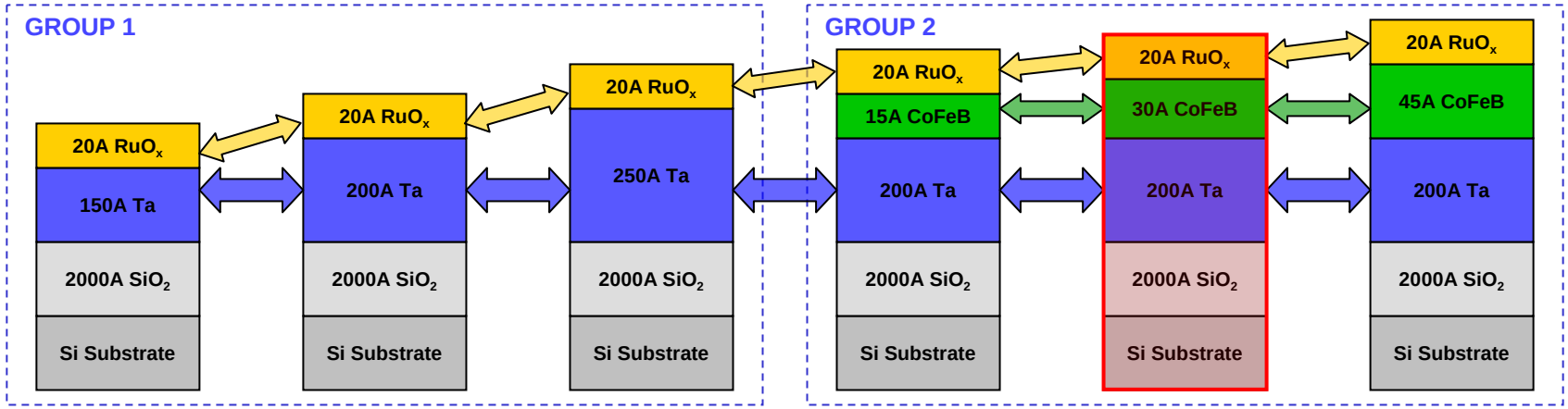


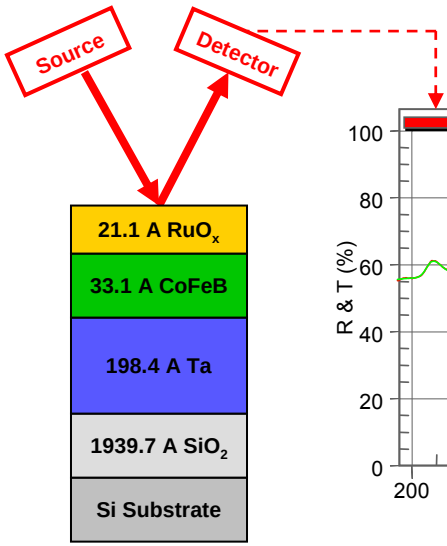


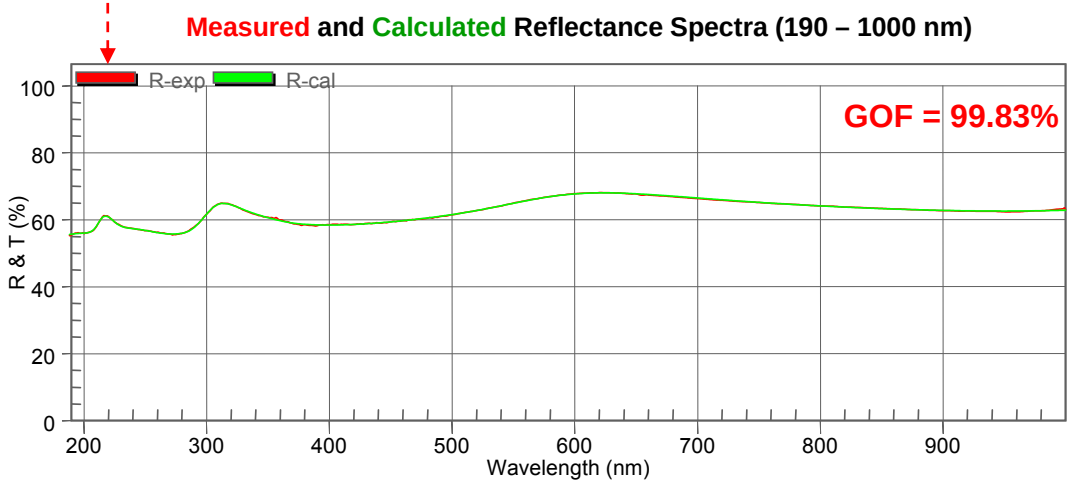


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 5

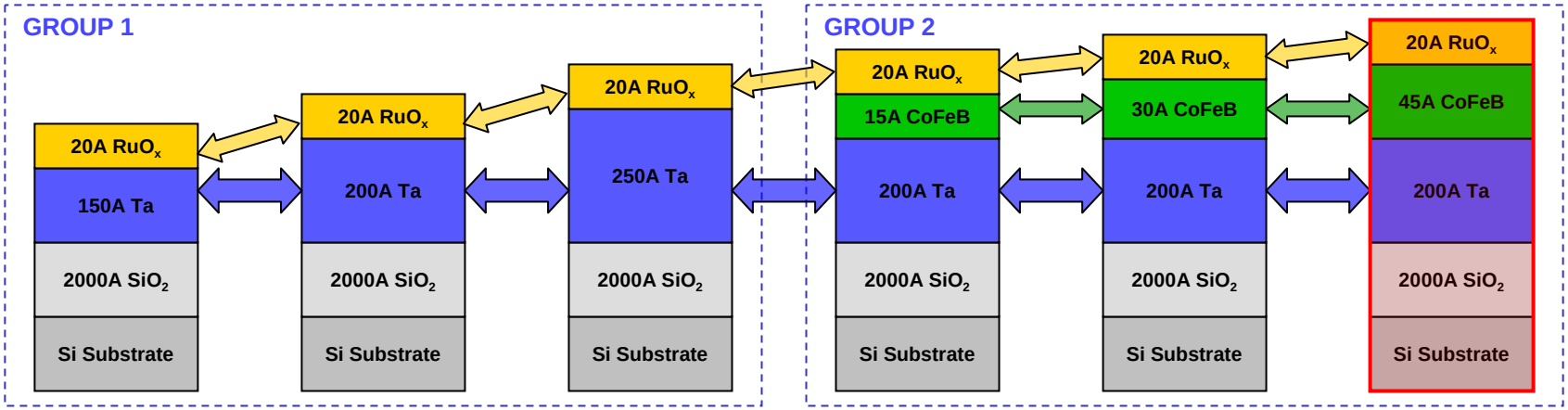


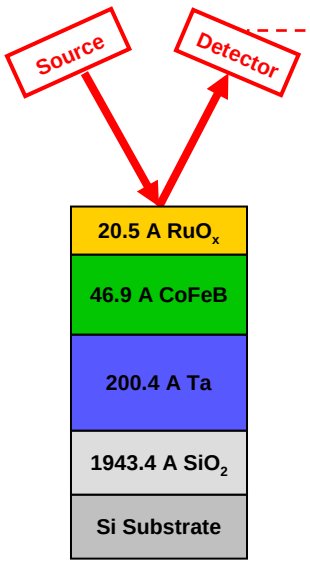


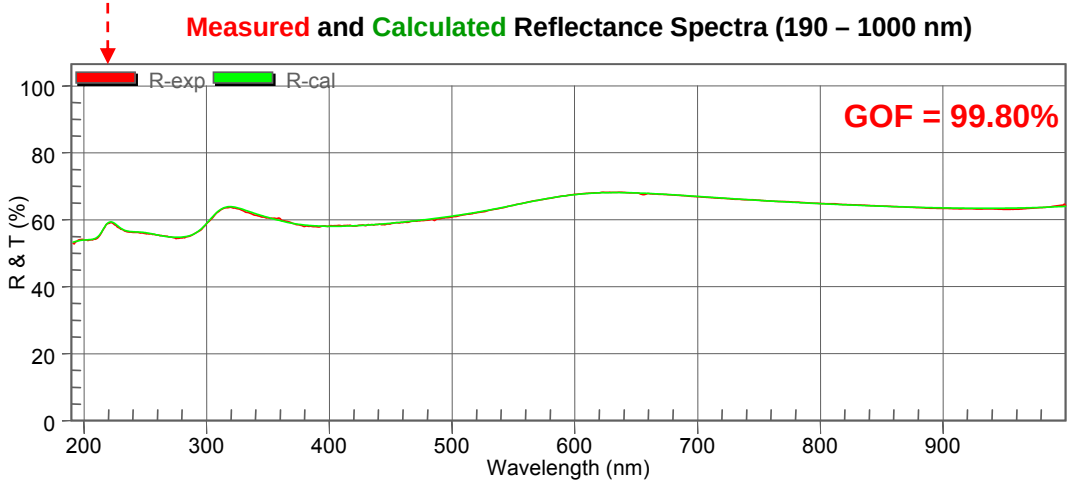


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 6

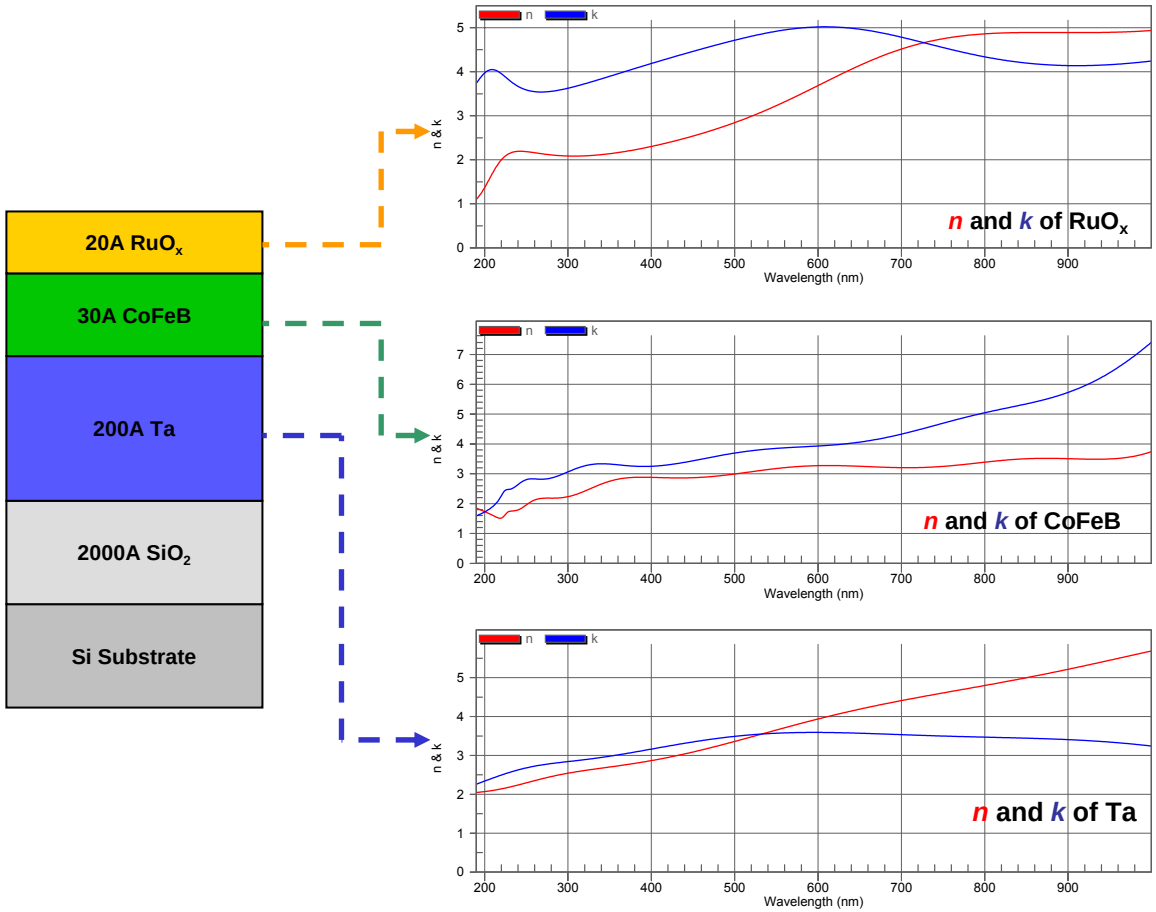






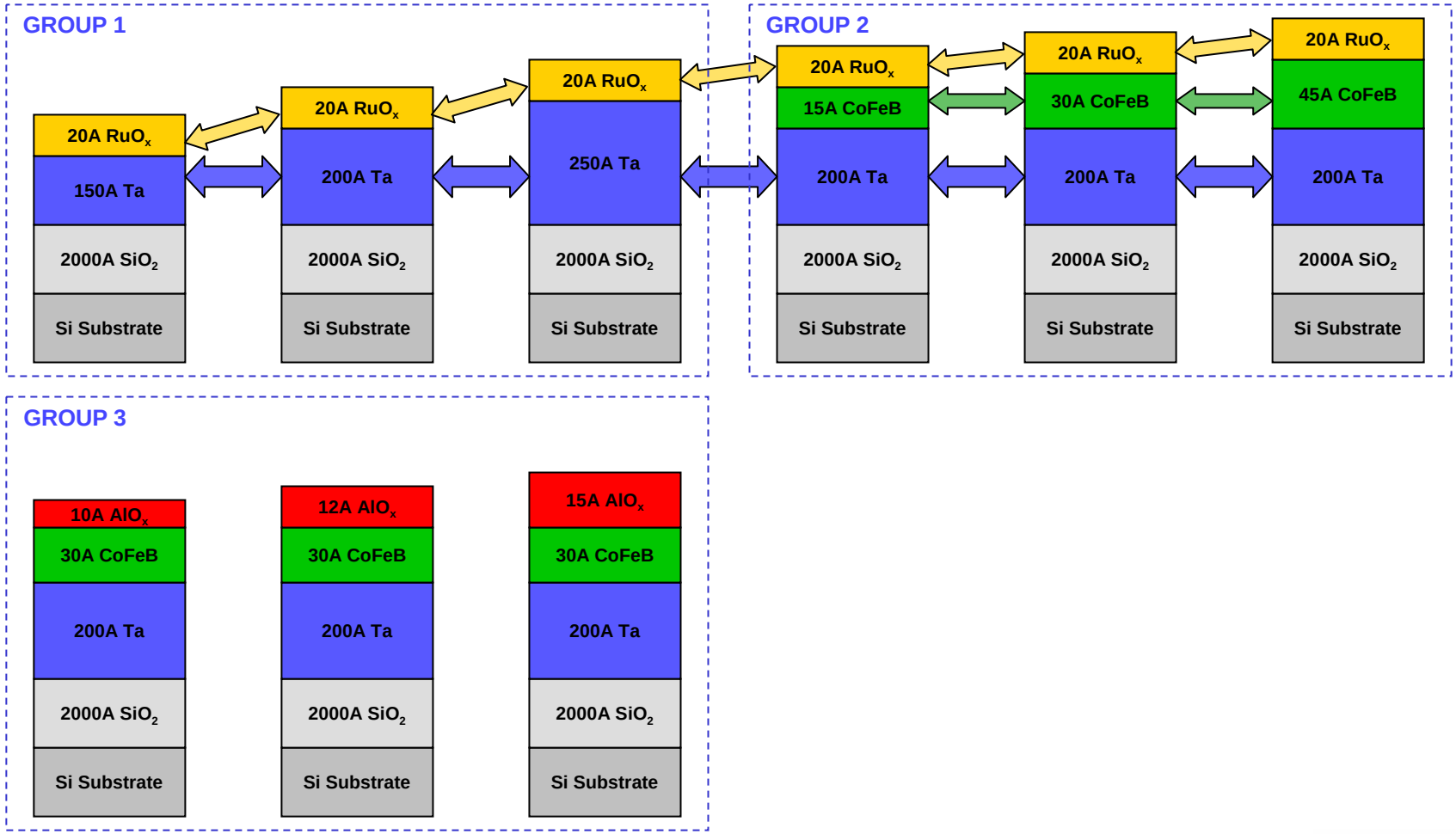
Analysis Results

Calculated *n* and *k* Spectra for Ta, CoFeB and RuO_x



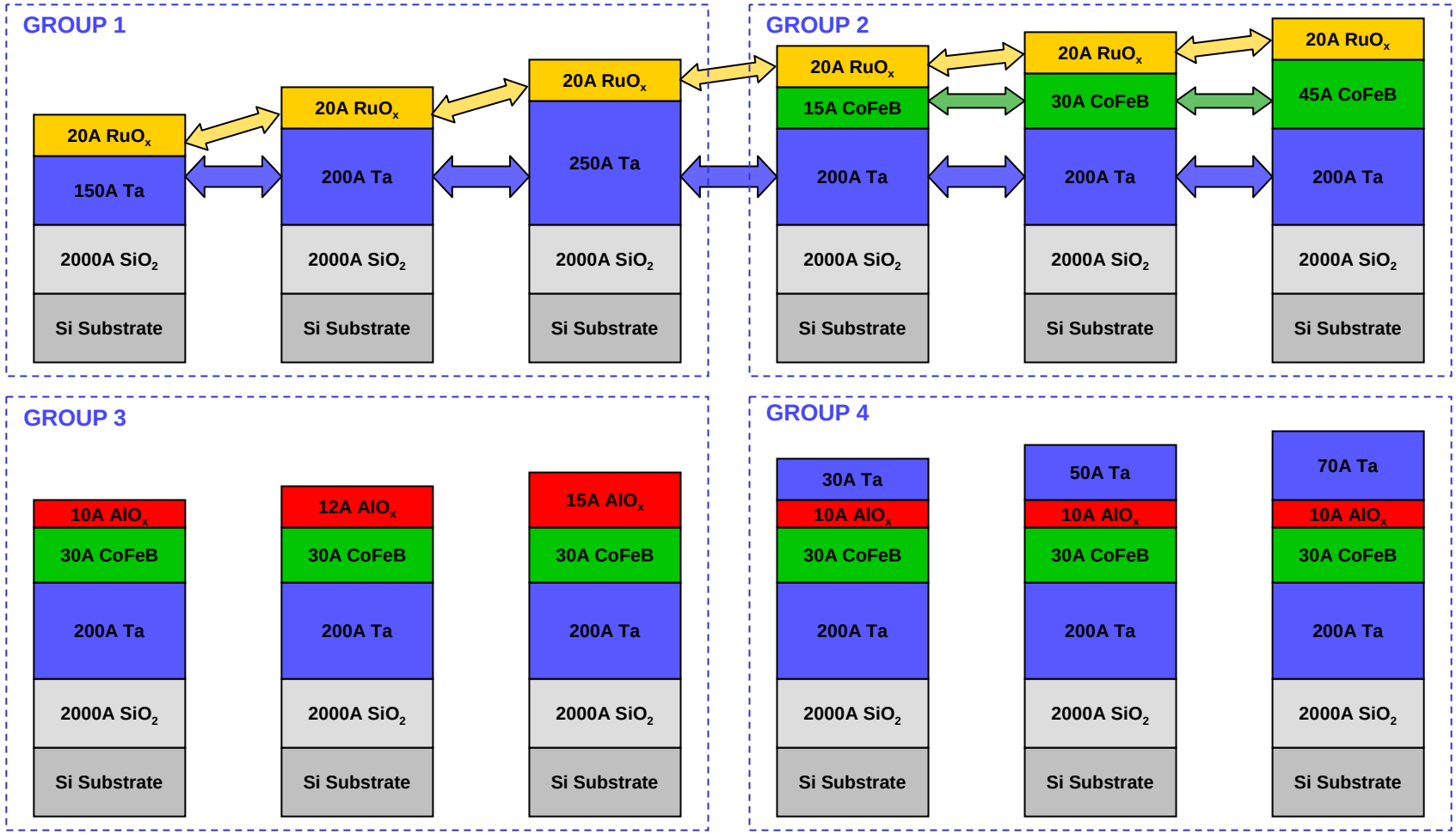
Background Samples

Sample Group 3: Used for Characterization of AlO_x



MRAM Samples

Sample Group 4: Used for Characterization of Ta Cap



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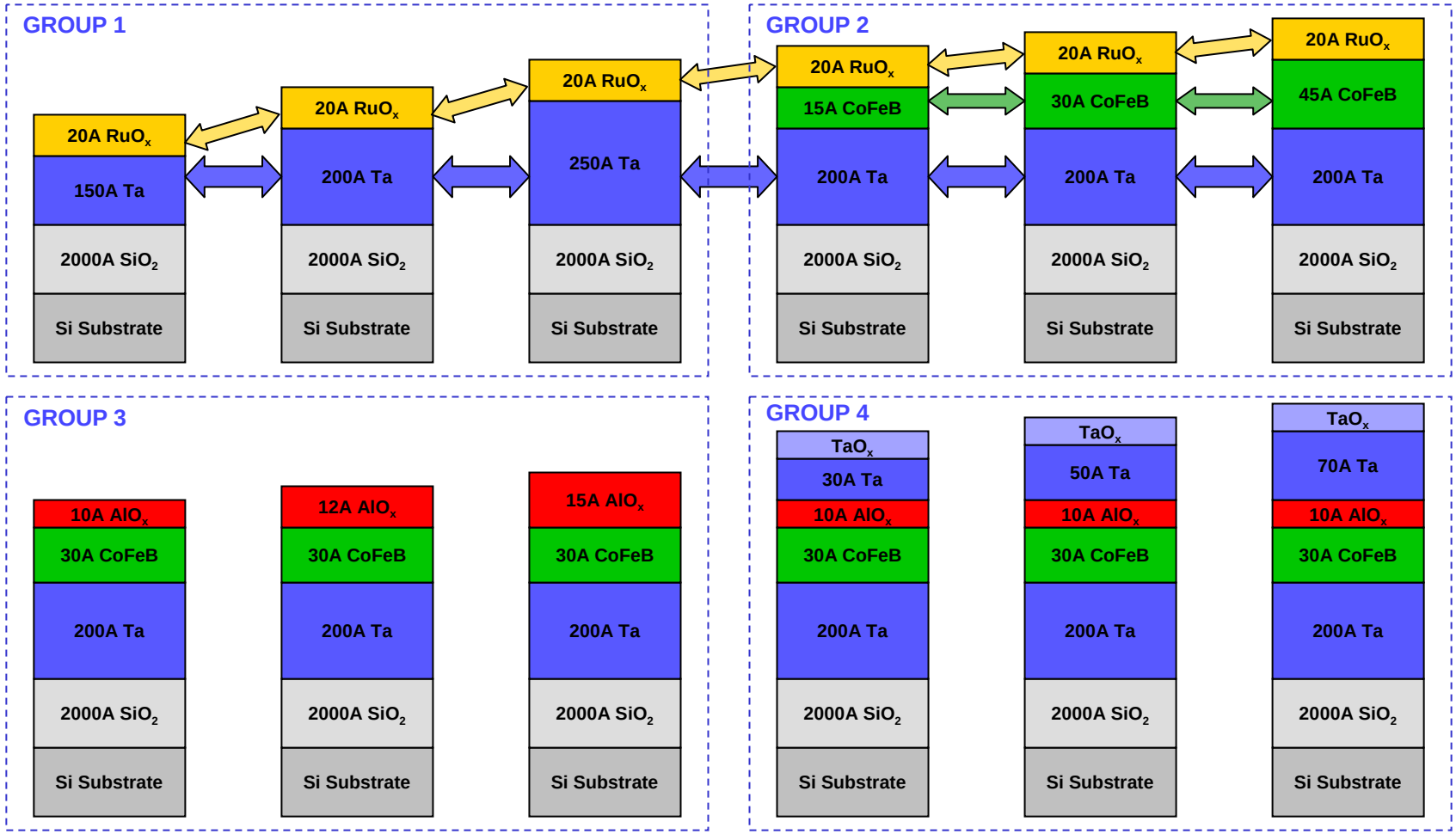
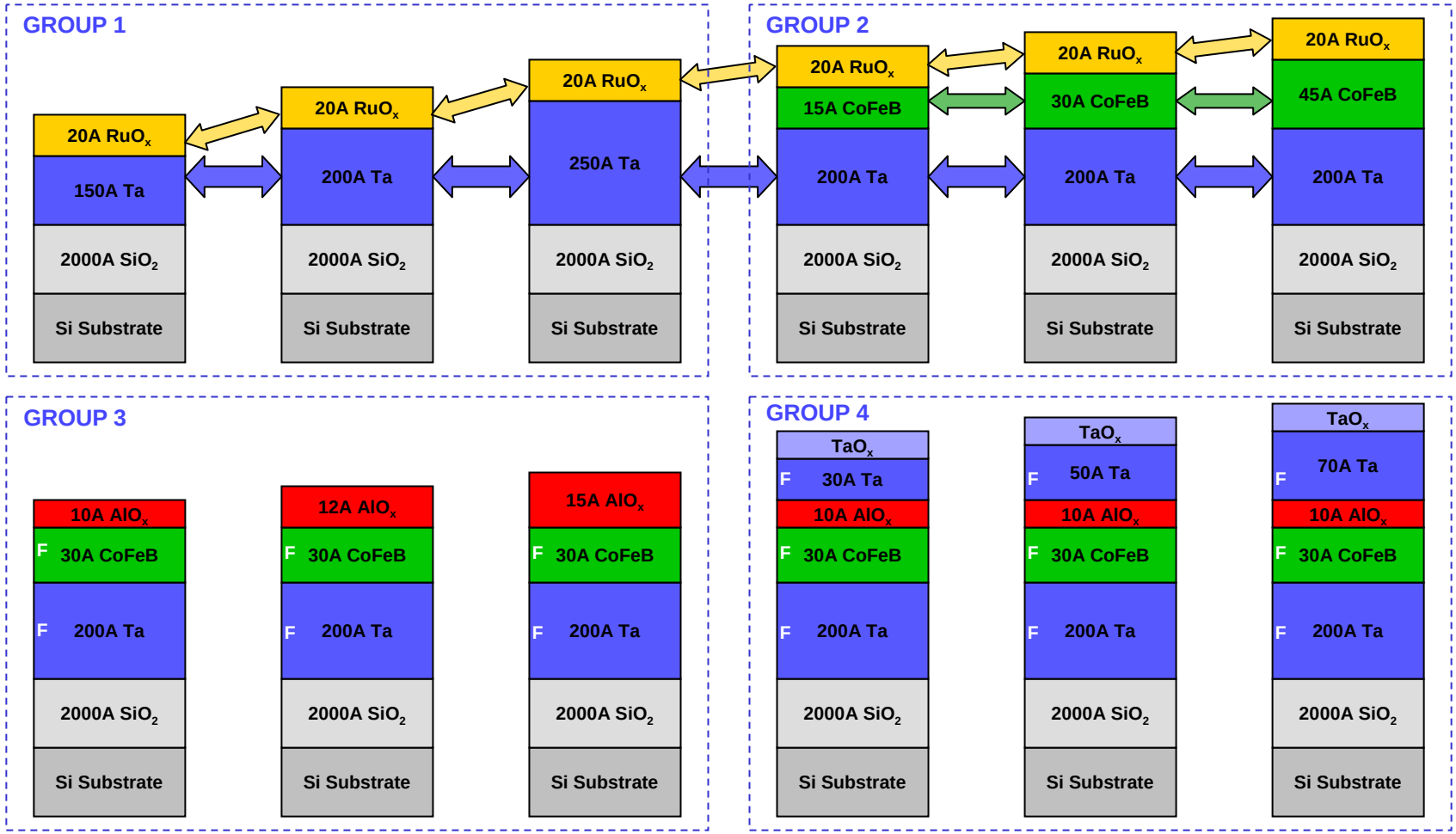
MRAM Samples

Sample Group 4: Used for Characterization of Ta Cap (with TaO_x)



Thin Film Characterization

Using Previously Determined *n* and *k* for Ta and CoFeB



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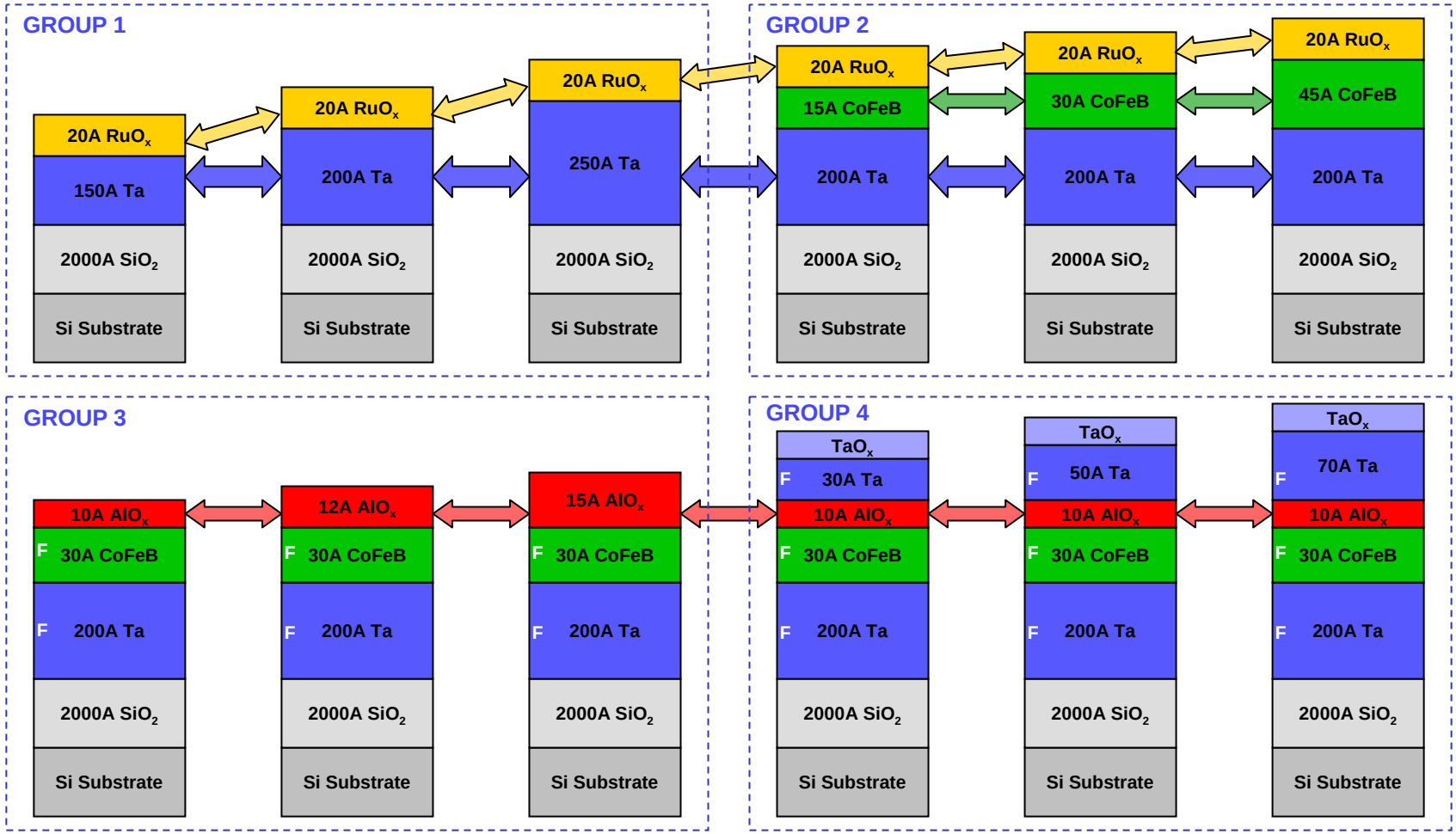
Thin Film Characterization

Coupling of Optical Properties (*n* and *k*): AlO_x



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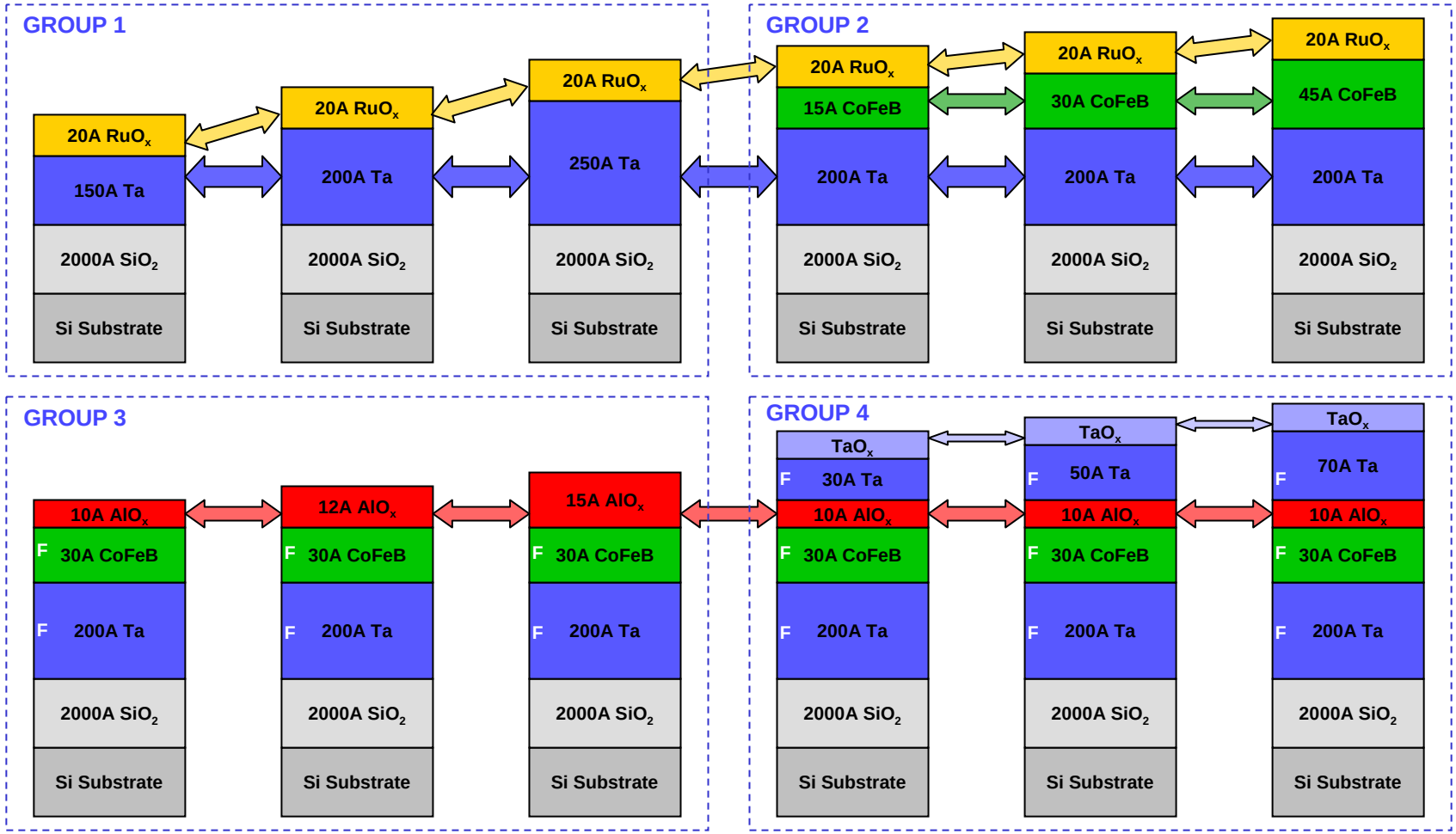
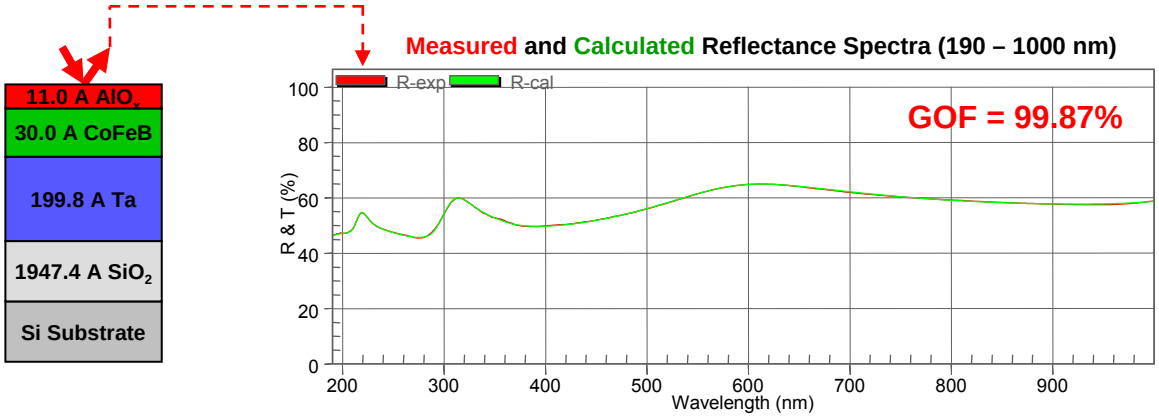
Thin Film Characterization

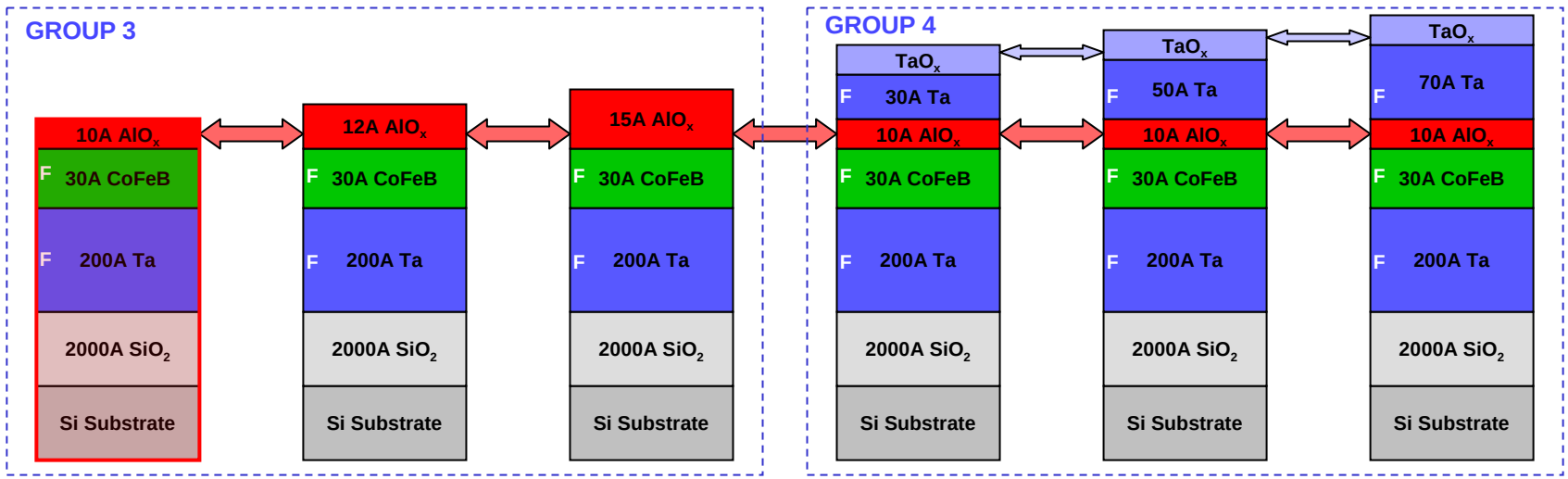
Coupling of Optical Properties (*n* and *k*): TaO_x



Analysis of Reflectance Spectra

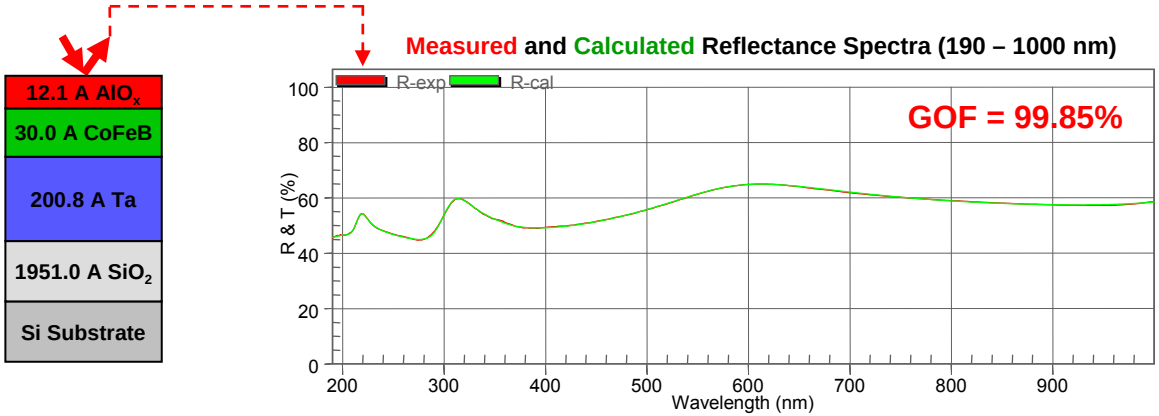
Simultaneous Analysis of all 6 Samples: Sample 7

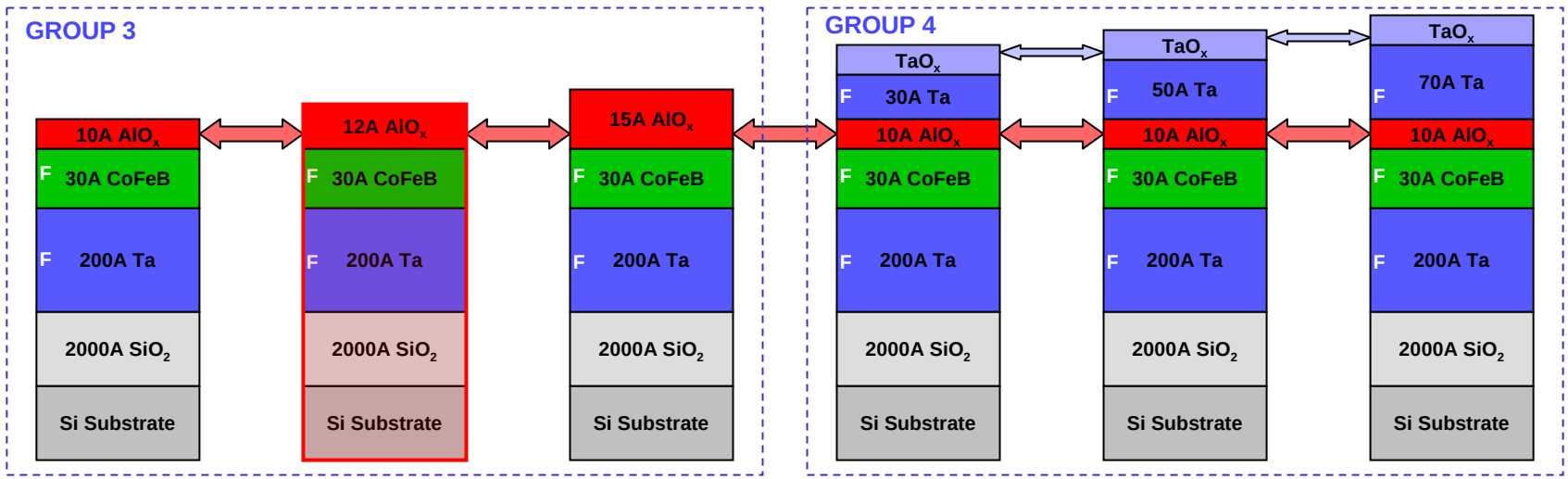




Analysis of Reflectance Spectra

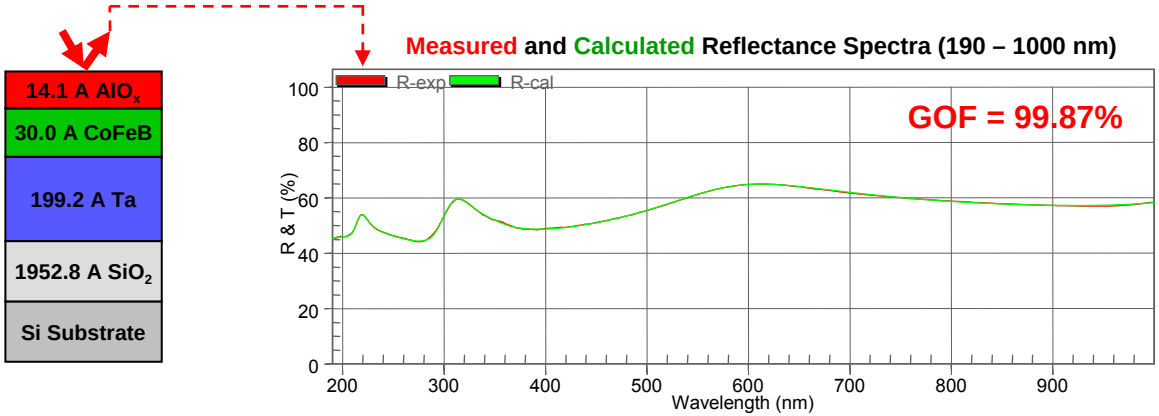
Simultaneous Analysis of all 6 Samples: Sample 8

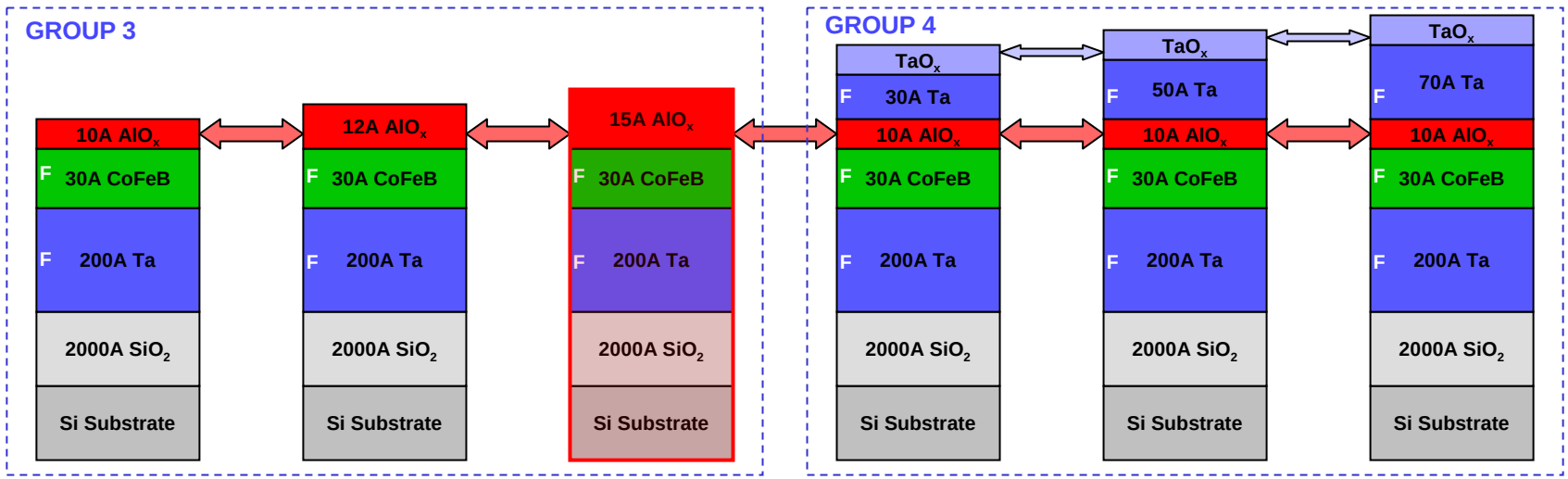




Analysis of Reflectance Spectra

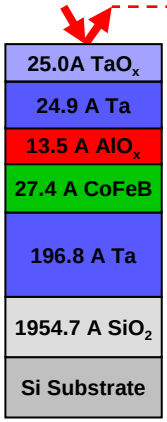
Simultaneous Analysis of all 6 Samples: Sample 9

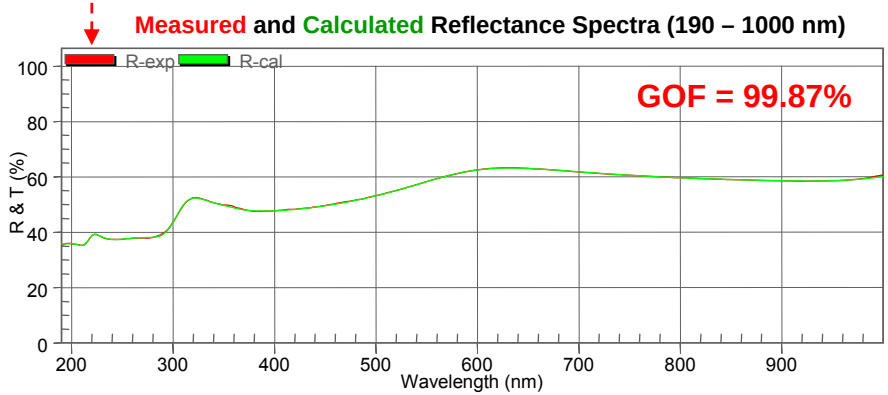


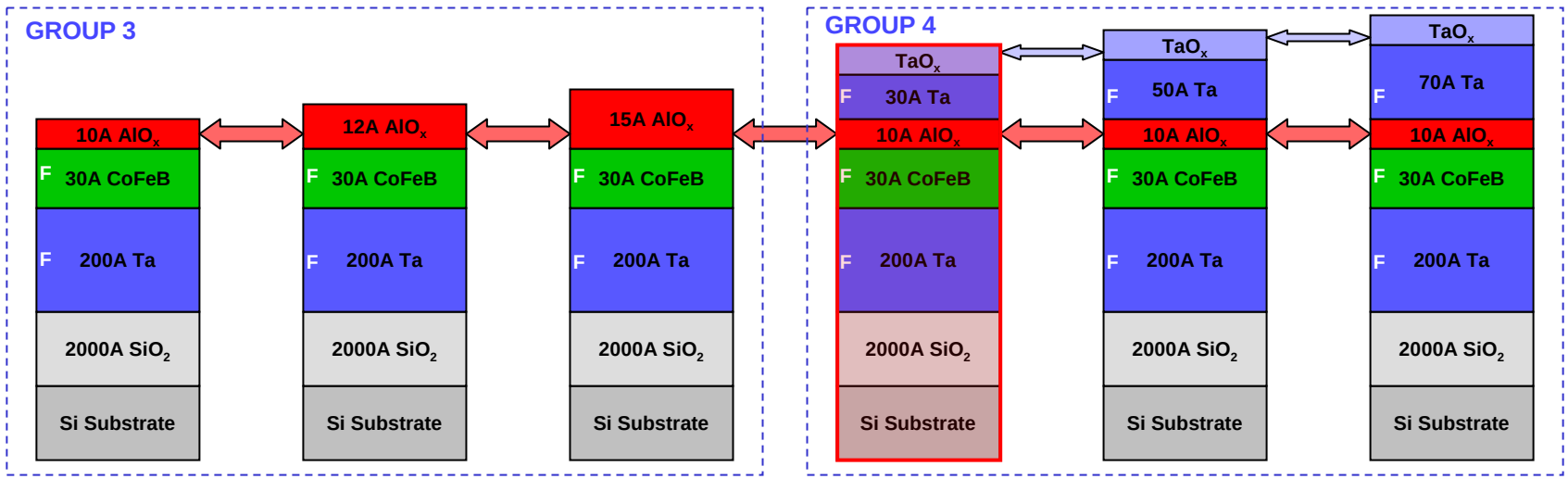


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 10

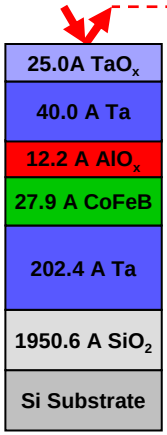


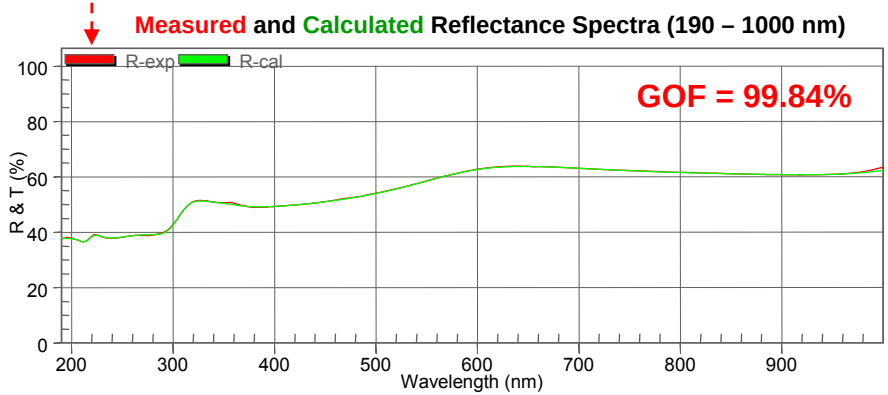


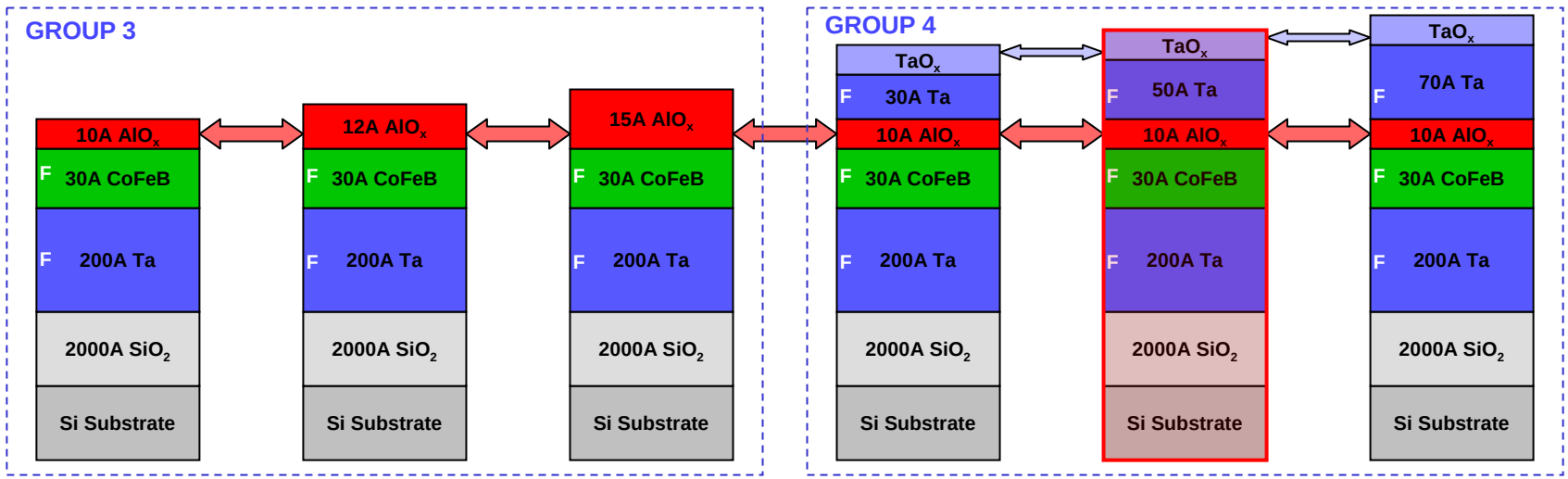


Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 11







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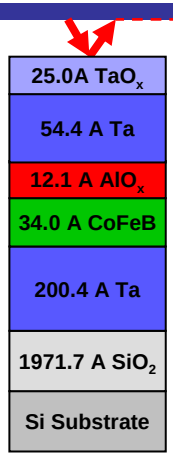
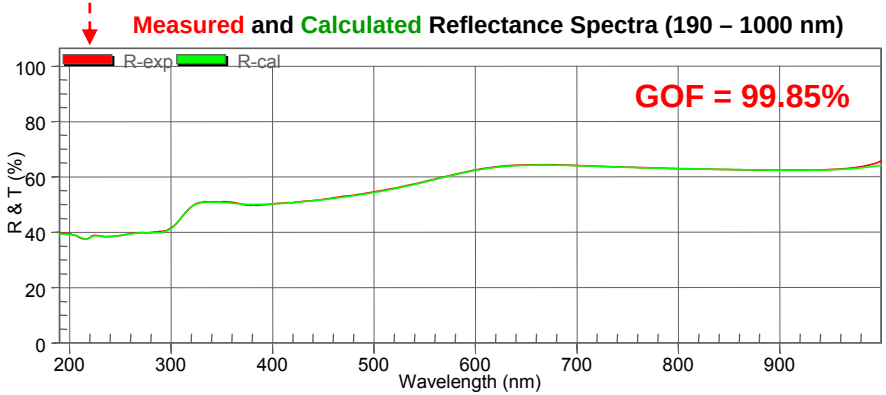
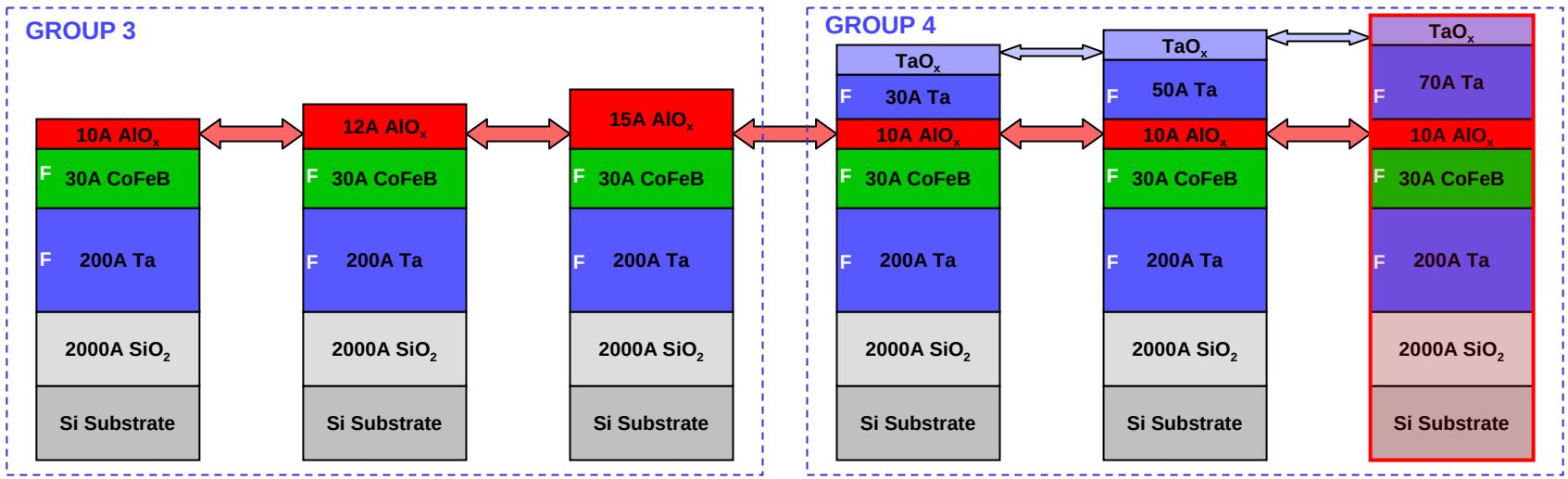
Analysis of Reflectance Spectra

Simultaneous Analysis of all 6 Samples: Sample 12

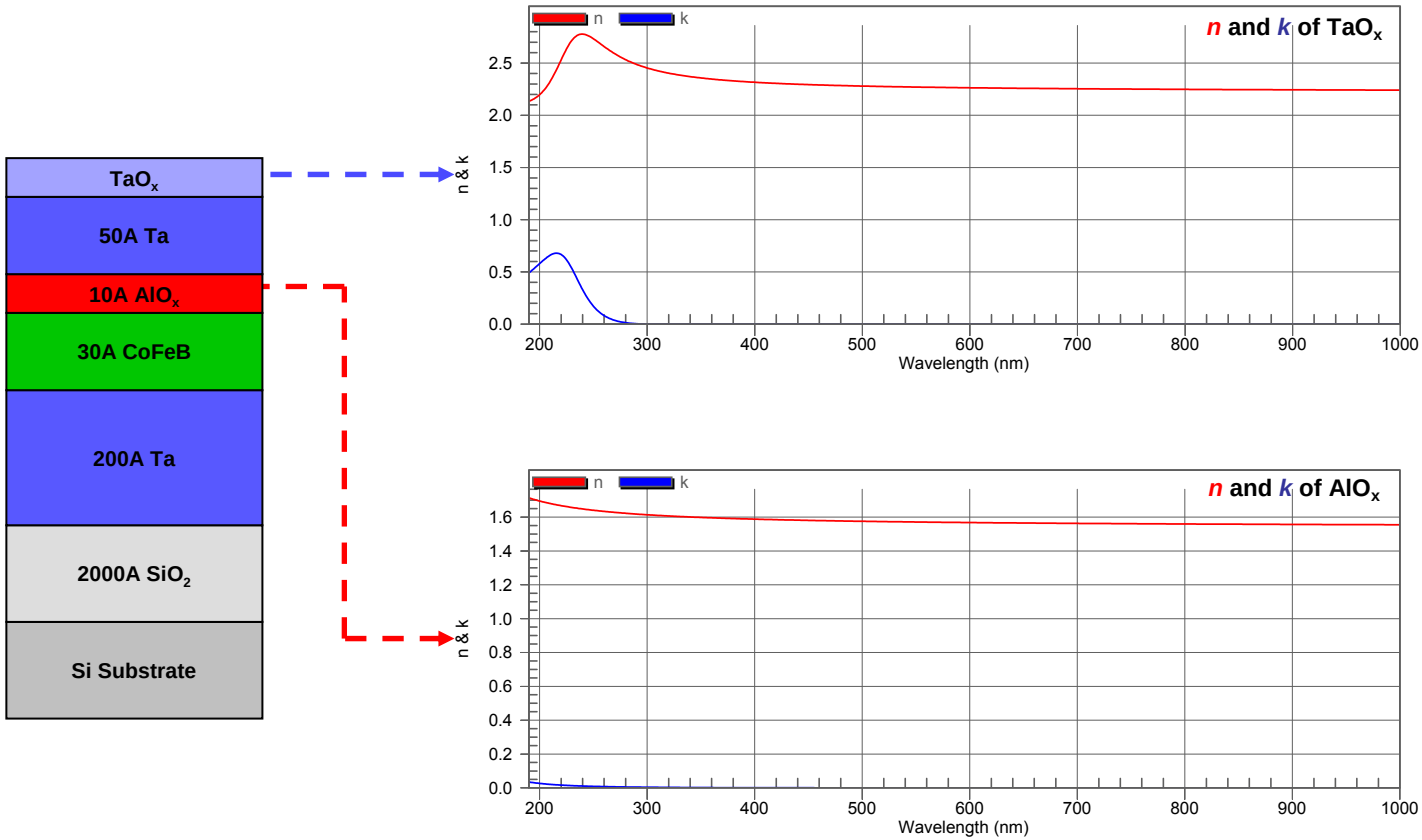






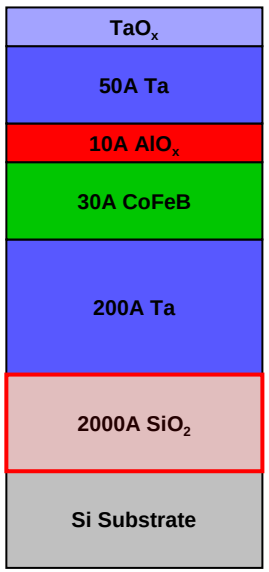
Analysis Results

Calculated *n* and *k* Spectra for TaO_x and AlO_x

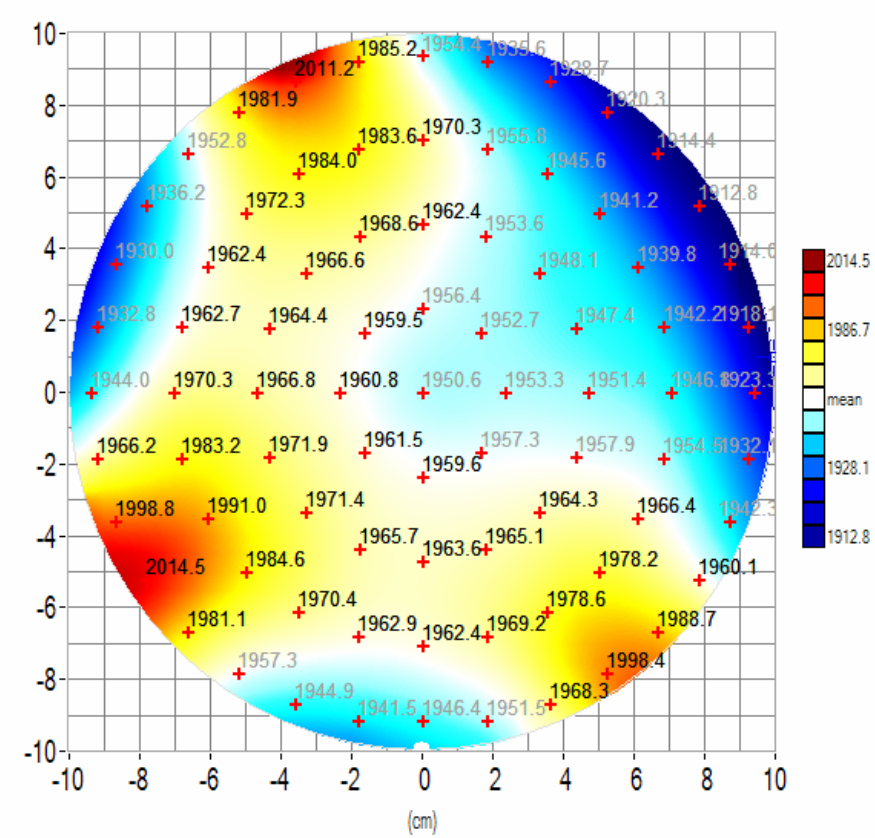


Analysis Results

Thickness Uniformity of All Layers: SiO_2



SiO_2 Thickness Uniformity Map



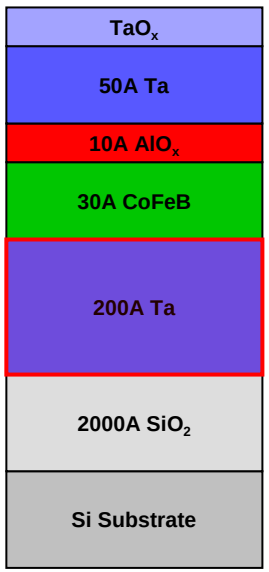
Statistics:

Min: 1912.8 Å
Mean: 1958.9 Å
Max: 2014.5 Å

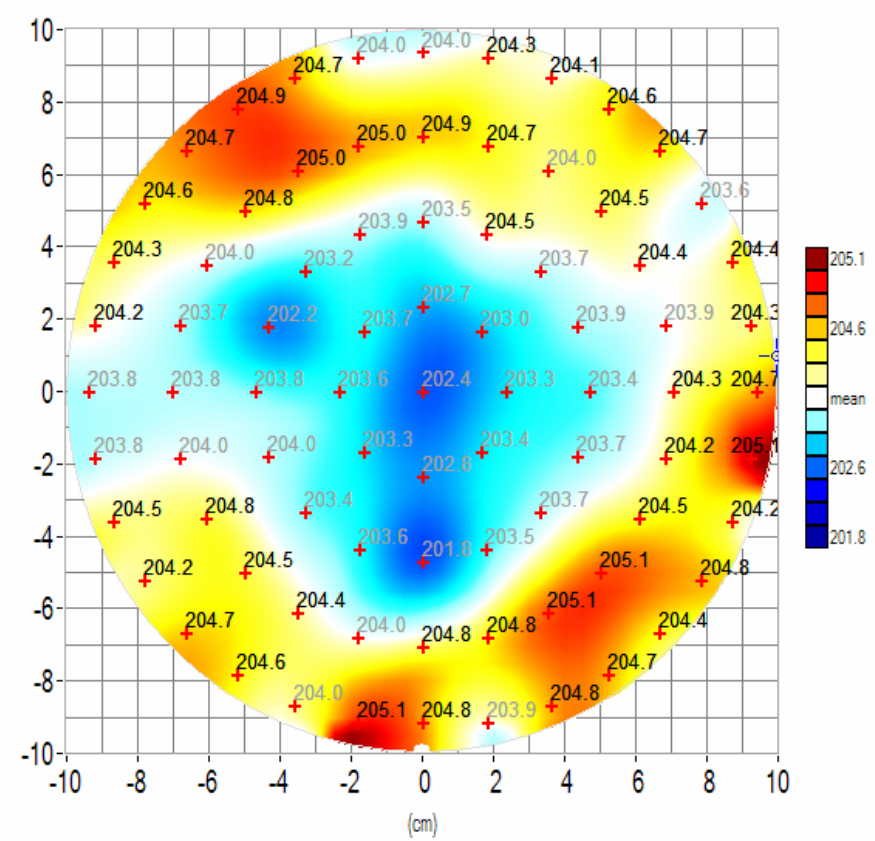
1σ Std. Dev.: 21.0 Å

Analysis Results

Thickness Uniformity of All Layers: Ta



Ta Thickness Uniformity Map



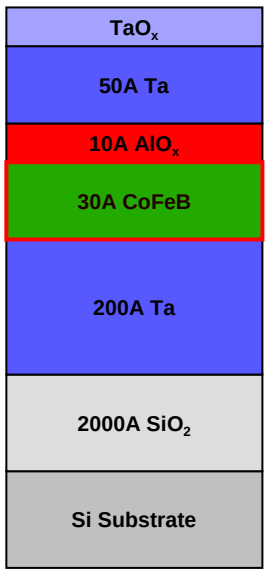
Statistics:

Min: 201.8 Å
Mean: 204.1 Å
Max: 205.1 Å

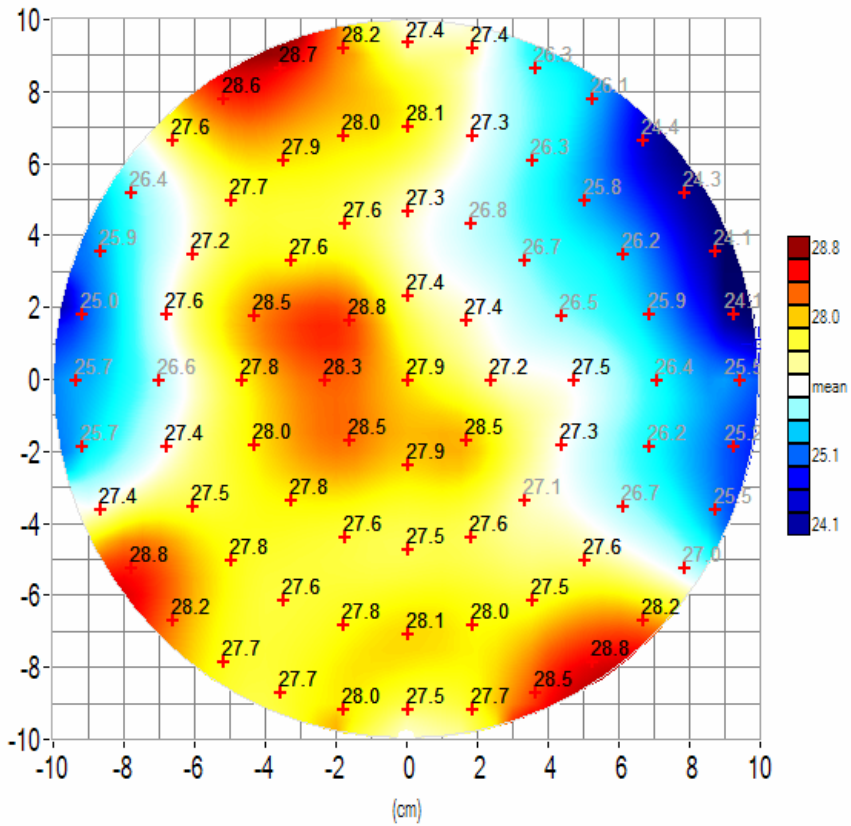
1σ Std. Dev.: 0.7 Å

Analysis Results

Thickness Uniformity of All Layers: CoFeB



CoFeB Thickness Uniformity Map



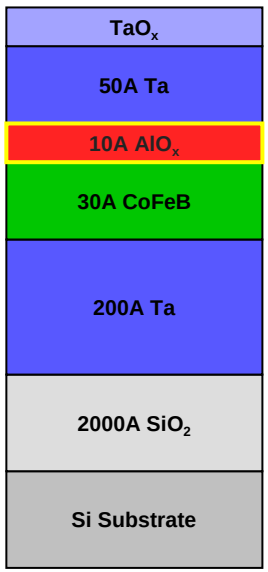
Statistics:

Min: 24.1 Å
Mean: 27.2 Å
Max: 28.8 Å

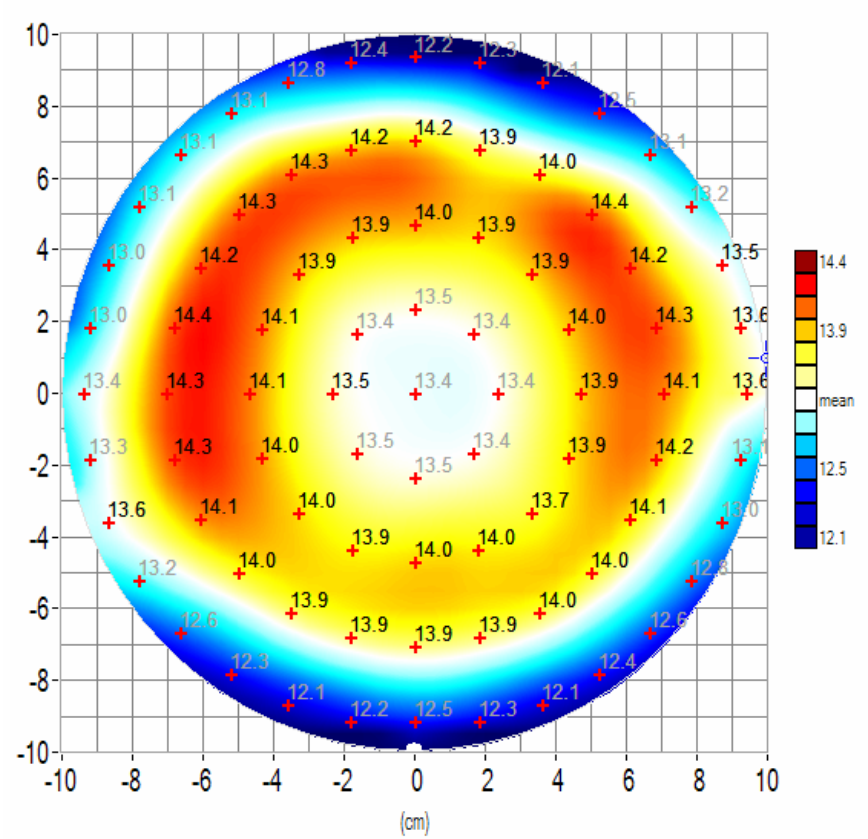
1σ Std. Dev.: 1.1 Å

Analysis Results

Thickness Uniformity of All Layers: Plasma-Oxidized AlO_x



Plasma-Oxidized Al Thickness Uniformity Map



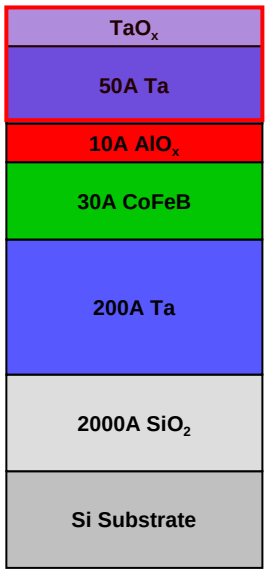
Statistics:

Min: 12.1 Å
Mean: 13.5 Å
Max: 14.4 Å

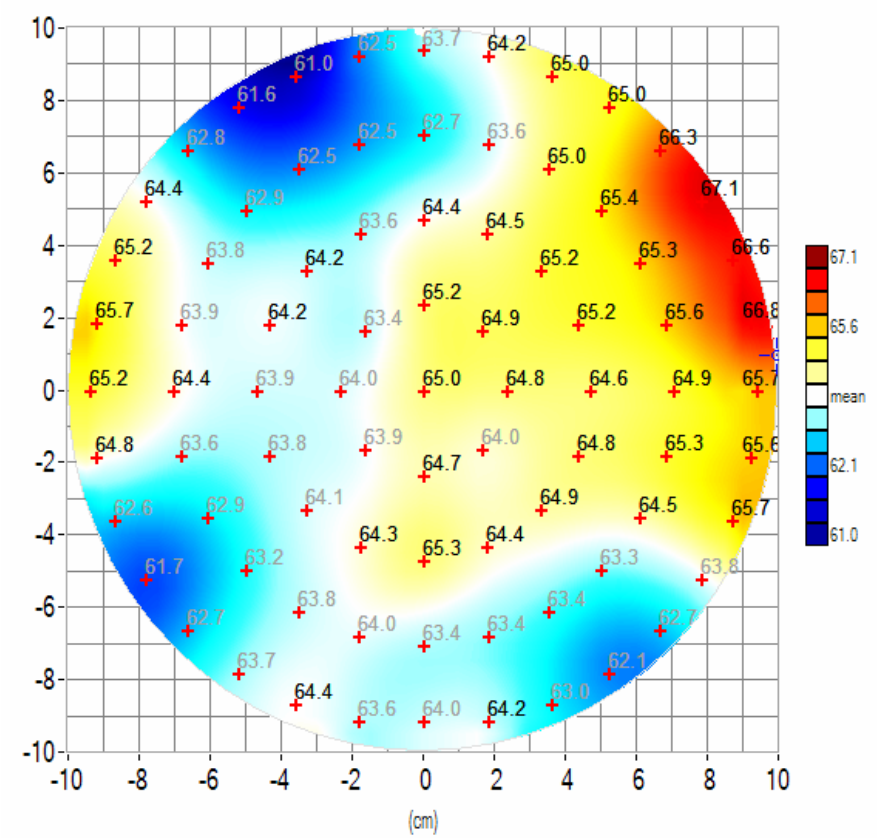
1σ Std. Dev.: 0.7 Å

Analysis Results

Thickness Uniformity of All Layers: Oxidized Ta



Oxidized Ta Thickness Uniformity Map



Statistics:

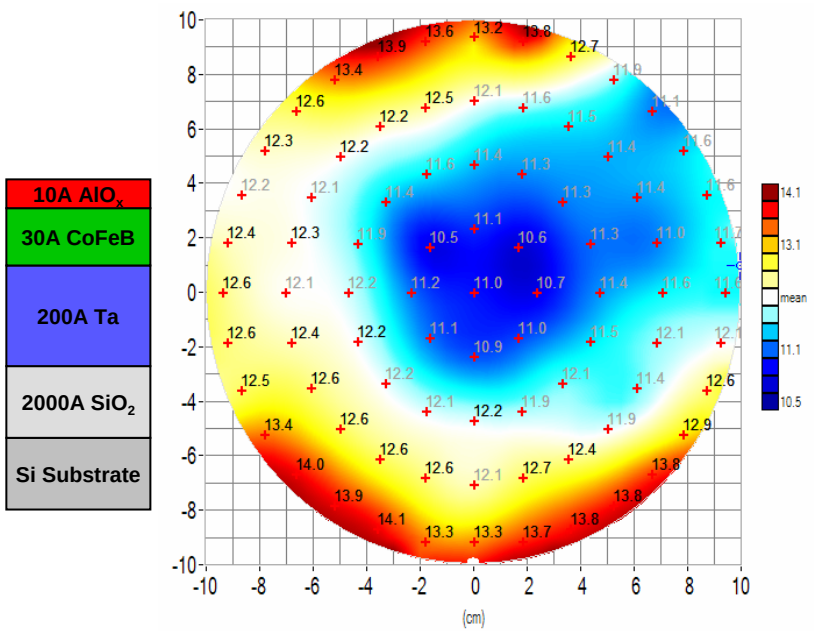
Min: 61.0 Å
Mean: 64.2 Å
Max: 67.1 Å

1σ Std. Dev.: 1.2 Å

Thickness Uniformity Comparison

Naturally-Oxidized Aluminum and Plasma-Oxidized Aluminum

Naturally Oxidized Aluminum

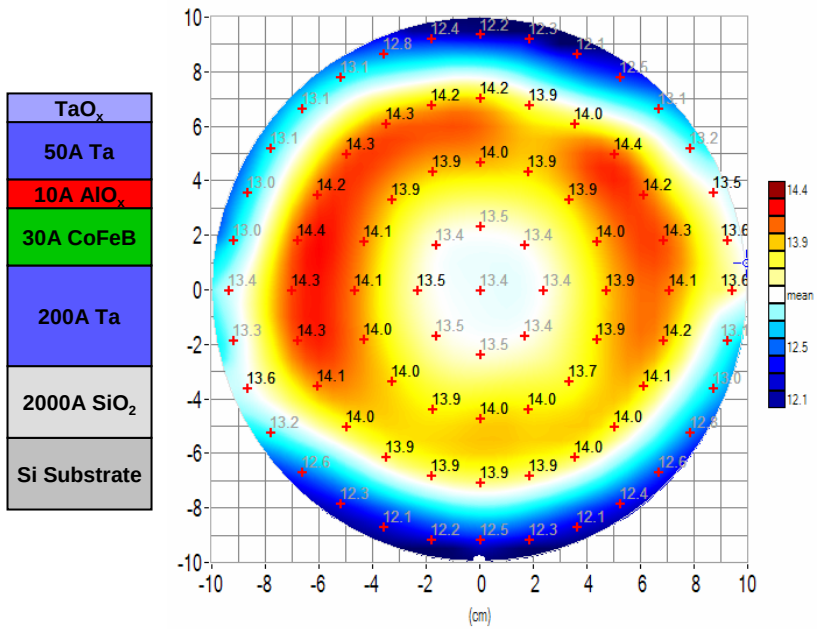


Statistics:

Min: 10.5 Å
Mean: 12.2 Å
Max: 14.1 Å

1σ Std. Dev.: 0.9 Å

Plasma-Oxidized Aluminum



Statistics:

Min: 12.1 Å
Mean: 13.5 Å
Max: 14.4 Å

1σ Std. Dev.: 0.7 Å

Conclusion

- **Using broadband reflectometry and the Forouhi-Bloomer dispersion relations complex multi-layer MRAM film structures were analyzed over a wavelength range of 190 to 1000 nm.**

- **A patented analysis method was used to analyze six unique Reflectance spectra simultaneously, in order to obtain the thicknesses, index of refraction (*n*) and extinction coefficient (*k*) of all layers.**

- **The thicknesses of all films (including the ultra-thin AlO_x layer) were measured simultaneously with a high degree of accuracy and resolution.**

- **The difference in thickness uniformity of naturally-oxidized Aluminum and plasma-oxidized Aluminum was characterized with a high degree of resolution.**

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