The Development of X-ray Metrology for Thin Film Thickness in Semiconductor Inspection

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Abstract

Accurate and reliable monitoring of different thin film thickness is critical to quality of the chips in the advanced microelectronic devices. A soft X-ray reflecitivity was developed to monitor the film thickness for the production of nanoscale thin films. The soft X-ray reflectivity with an Al source was constructed to provide accurate thickness measurements, and small footprint on film surface, since X-ray reflectivity is very sensitive to surface and interface roughness, and also provides information about film density. Improvements in the soft x-ray reflectivity configuration were made to allow high throughput in line measurements on films as thin as 1.2 nm. Comparing to commercial XRR, our soft X-ray reflectivity system can increase incidence angle during reflectivity measurement. Because of this, not only was the measured area of our system down to 50x50 μm^2 but we also used the focused beam to increasing the flux for raising the signal to noise ratio. Improvements in the soft x-ray reflectivity configuration were made to allow high throughput in line measurements on films Therefore, non-destructive XRR method can be provided as a powerful metrology tool for its fast and accurate measurement.

Background

With the next technology node coming, accurate and reliable monitoring of different thin film thickness is critical to quality of the chips in the advanced microelectronic devices. In semiconductor industrial, the high-k/metal gate thickness will be reduced to several nanometers for improved performance, and the measured area will also be confine to several micrometers. However, the optical measurement can no longer provide sufficient resolution and measured area. A soft X-ray reflectivity was developed to monitor the film thickness for the production of nanoscale thin films.

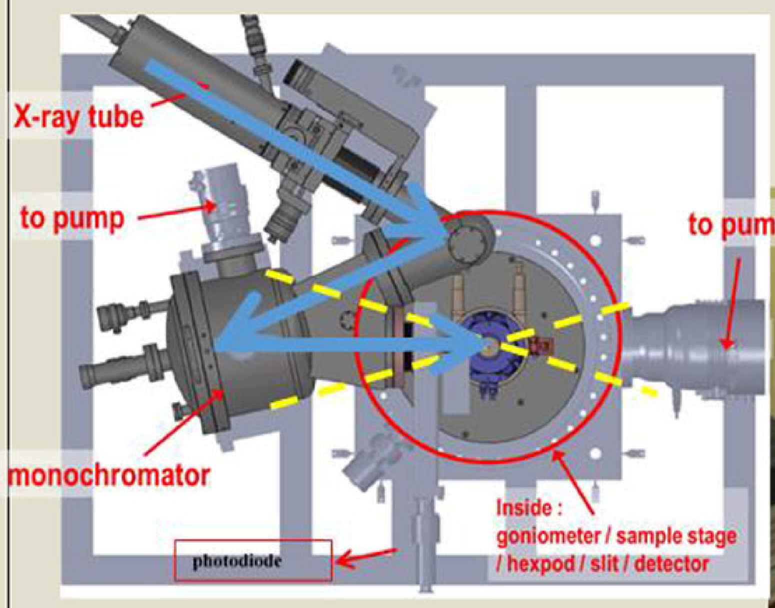
Methods

In this study, we developed the thin film thickness measurement system with an Al X-ray source which was constructed to provide accurate thickness measurements, and small footprint on film surface, since X-ray reflectivity is very sensitive to surface and interface roughness, and also provides information about film density. The configuration of the constructed soft x-ray reflectivity is shown below. The Al source can increase the incident angle during reflectivity measurement. As soft x-ray reflectivity already used anode Al source under grazing incidence and the variation of the angle of incidence, a θ-2θ goniometer was simulated by combining a photodiode and a Silicon Drift Detector (SDD). The photodiode is used to reduce the high count-rate of the direct and totally reflected beam at small angles, which exceeds the working range of the SDD.

Results

In this study, the target high-k and metal films (four samples: 1. HfO2 50 nm / SiO2 / nm/ Si substrate, 2. HfO2 2 nm / SiO2 / nm/ Si substrate, and 3. HfO2 1.2 nm / SiO2 / nm/ Si substrate, and 4. TaN 2.0 nm / SiO2 / nm/ Si substrate shown as TABLE 1) were deposited by atomic layer deposition (ALD). In this preliminary results, using this new setup to measure the thickness of high-k gate oxide (sample 1) is shown in below, incorporating TEM analyses. The TEM images show an unclear interface between each layer owing to the thickness and amorphous phase, therefore it is hard to actually define thickness. Besides, for comparing the difference of the commercial XRR and prototype XRR, we used the same sample to verify. Besides, in sample 3, the S/N ratio in high angle reflectivity measurement is better and the thickness of HfO2 layer is 1.22 nm.

The configuration of the constructed soft x-ray reflectivity



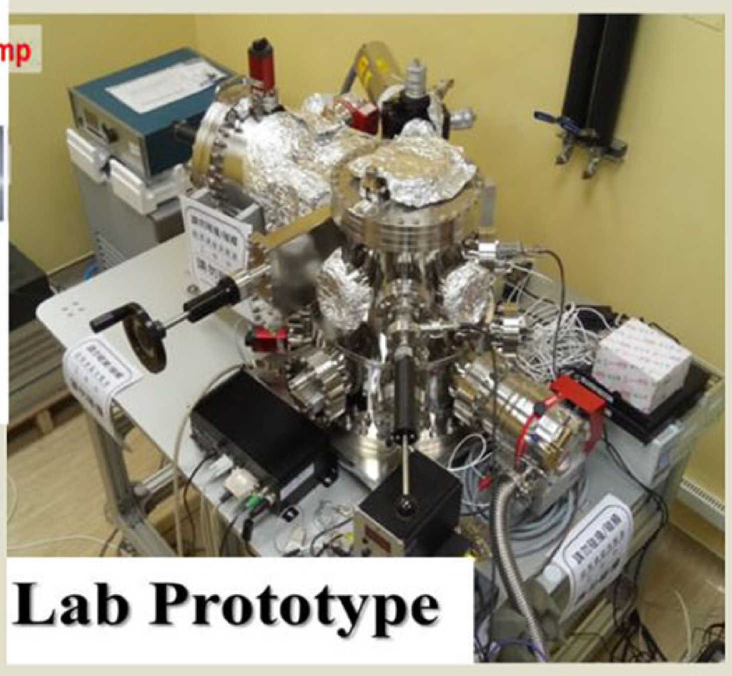
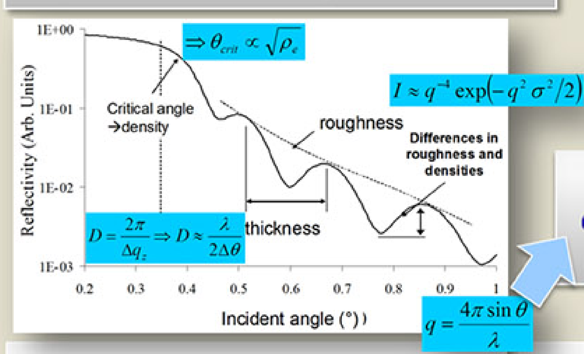


TABLE 1. The information of samples

Sample number	Sample structure	Sample thickness
1	$HfO_2/SiO_2/Si$	50 nm
2	$HfO_2/SiO_2/Si$	2 nm
3	$HfO_2/SiO_2/Si$	1.2 nm
4	$TaN/SiO_2/Si$	2 nm

Solution- Long Wavelength X-Ray Reflectometry

Wavelength increased as
Cu target → Al
λ = 1.54 Å → 8.38 Å
Interested angle range
θ = 3° → 16.5°

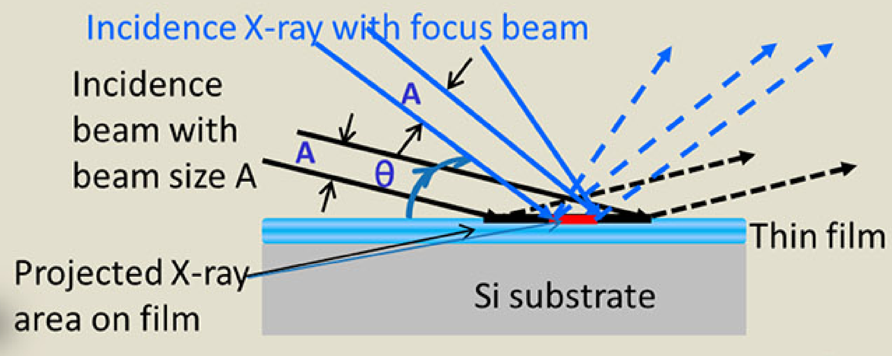


$\Rightarrow \theta_{crit} \propto \sqrt{\rho_e}$

$I \approx q^{-4}\exp(-q^2\sigma^2/2)$

$D = \frac{2\pi}{\Delta q_z} \Rightarrow D \approx \frac{\lambda}{2\Delta\theta}$

$q = \frac{4\pi\sin\theta}{\lambda}$



$$q = \frac{4\pi\sin\theta}{\lambda} \xrightarrow{\text{Keep resolution}} \frac{\delta q}{q} = c = \frac{\cos\theta\cdot\delta\theta}{\sin\theta} - \frac{\delta\lambda}{\lambda}$$

Footprint reduction (if incident beam width is 10 μm)

$$\frac{10}{\sin 3^\circ} = 191\,\mu m$$

$$\rightarrow \frac{10}{\sin 16.5^\circ} = 35.2\,\mu m$$

- δθ can be opened up **5.6 times (19.1/3.4)**
- **Focused beam** with more flux

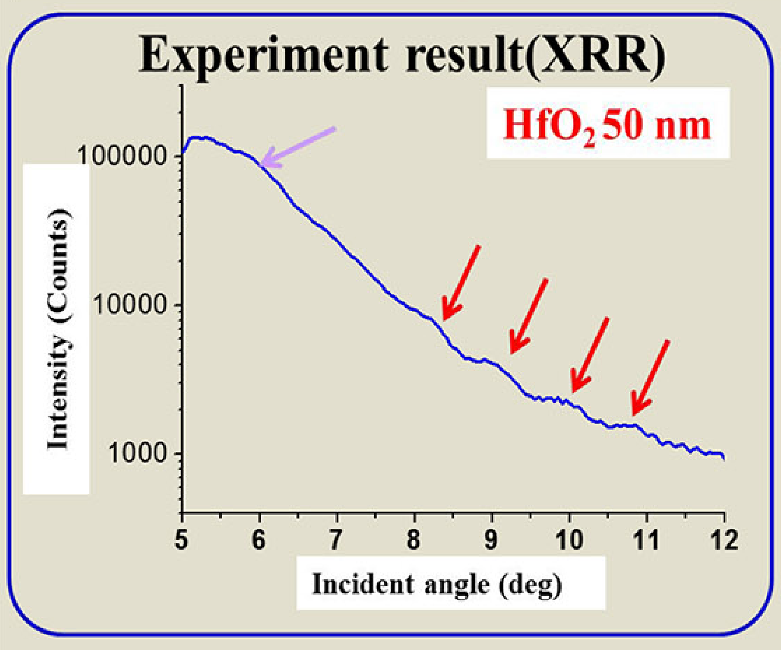
$$\cos 3^\circ / \sin 3^\circ = 19.1$$

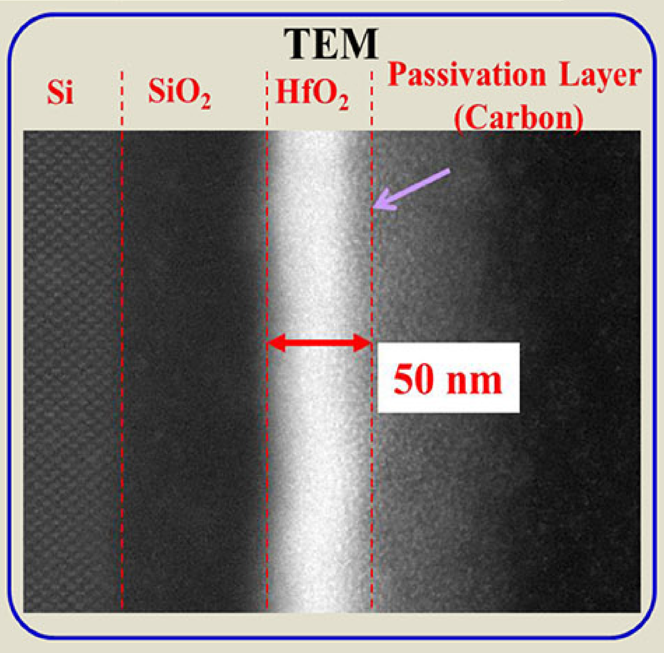
$$\cos 16.5^\circ / \sin 16.5^\circ = 3.4$$

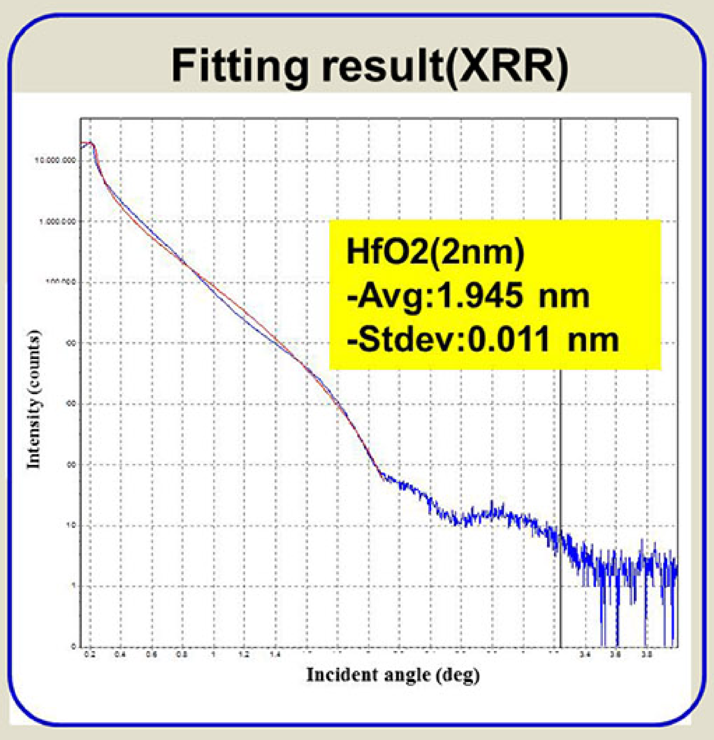
Obtain enough intensity

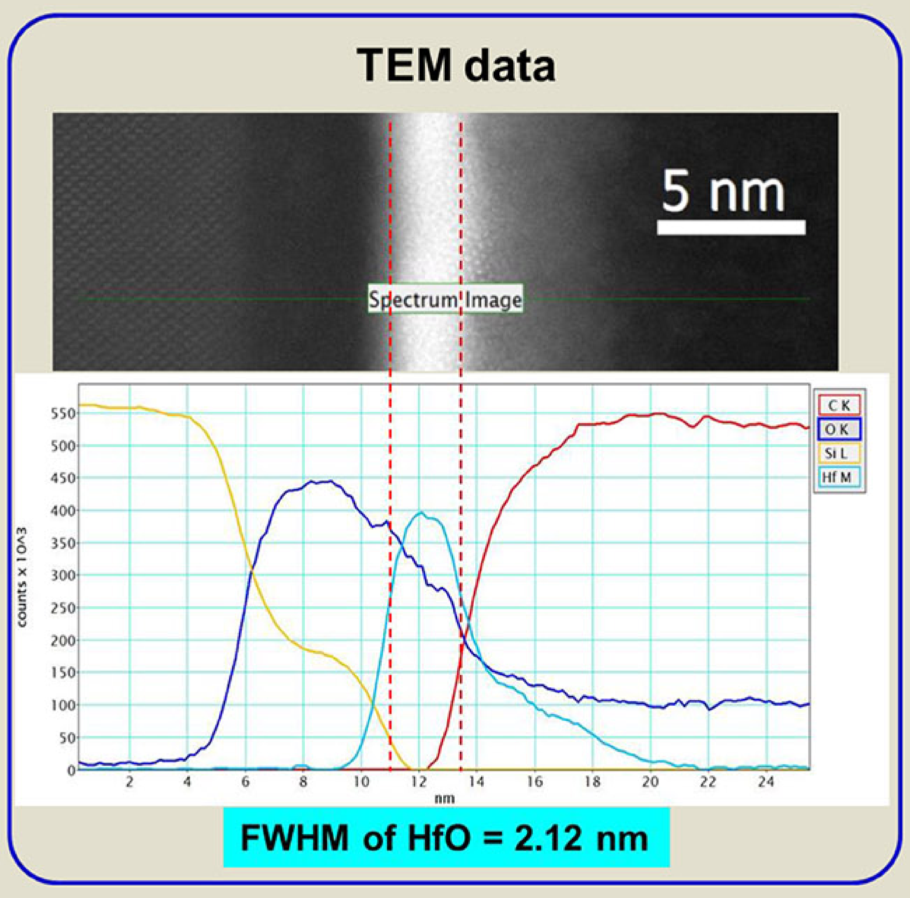
- **Mirror** replace Si monochromator
- **Open up (δλ/λ)** to increase intensity without losing resolution

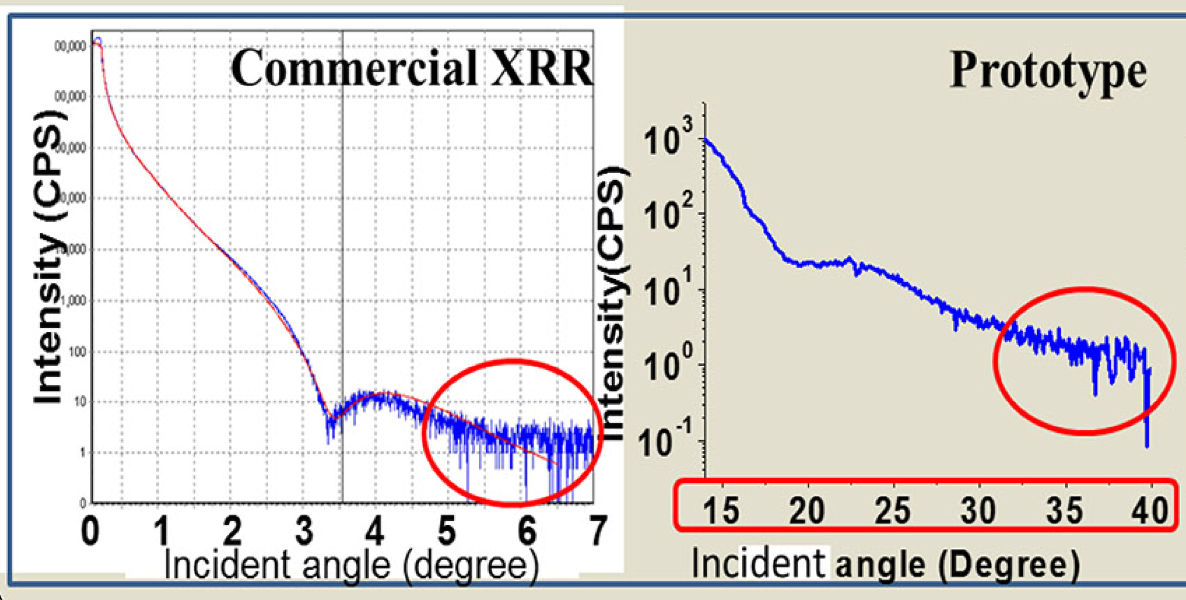
Sample structure:











Method	HfO_2 Thickness
Commercial XRR (Cu target)	1.29 nm
Long wavelength XRR (Al target)	1.22 nm

Conclusion

- ***Long Wavelength inline XRR***
- Metrology precision ~ 0.002 nm
- Thickness sensitivity ~1 nm
- Footprint is reduced to ~ 50 μm
- Thickness range: 1 nm ~ 50 nm
- Focused beam increase flux: reduced background noise
- Throughput can managed down to 1 min

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