From Large Research Instruments To An Industrial Control: X-ray Photoelectron Spectroscopy Characterizations Of Advanced Technology Gate Stack.

L. Fauquier[1,2,3], B. Pelissier[2,3], J. Avila[4], M.-C. Asensio[4], D. Le Cunff[1], D. Doloy[1], C. Beitia[2,5] and T. Baron[2,3]

[1] **STMicroelectronics,** 850 Rue Jean Monnet, 38920 Crolles, France
[2] **Univ. Grenoble Alpes**, F-38000 Grenoble, France
[3] **CNRS, LTM, MINATEC Campus**, F-38054 Grenoble, France
[4] **Synchrotron SOLEIL**, Saint Aubin, BP 48 91192 Gif-sur-Yvette, France
[5] **CEA, LETI, MINATEC Campus**, F-38054 Grenoble, France

Introduction

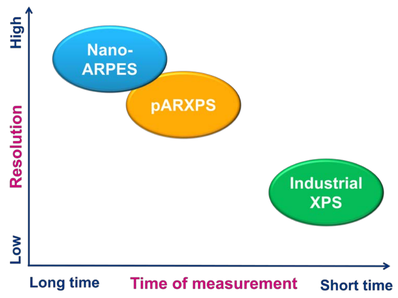
Since 32nm node, SiO_2 gate insulator has been replaced by **High-k Metal Gate (HKMG)** film stack [1]. For 14nm node, this HKMG stack is composed of a high-κ **HfON** layer deposited on a **SiON** interfacial layer (IL), to prevent the formation of a bad quality SiO_2 layer between the HfON layer and the channel [2]. To reach the transistor specifications, thickness and composition of the different deposited layers must be precisely controlled. For HKMG stack, the **amount of nitrogen** in the HfON and SiON layers is specifically critical.

In this work, three different XPS configurations used to characterize the same **HKMG stack** composed of a **20Å HfON layer** on a **10Å SiON interfacial layer**:

- a **Nano Angle Resolved Photoelectron Spectroscopy (Nano-ARPES)** system using the SOLEIL synchrotron ANTARES beam line [3],

- a **Thermo Fisher Scientific laboratory parallel Angle Resolved XPS (pARXPS)** system,

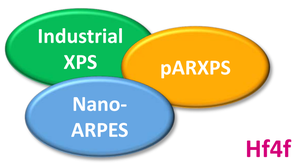
- an **in-line commercial industrial VeraFlex II system**.



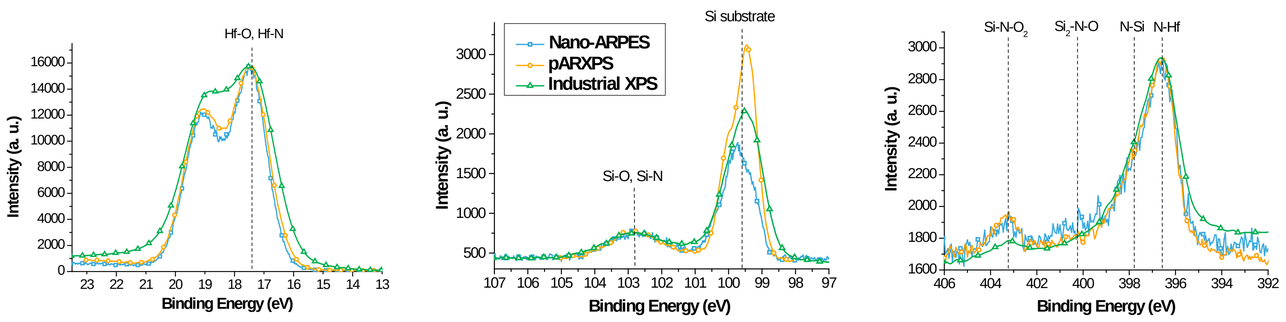
Comparison of the three XPS capabilities based on resolution and time of measurement.

Nano-ARPES and **pARXPS**, thanks to the angular information, can provide **depth resolved information** on chemical state of near-surface layers [4]. **In-line XPS**, optimized for an **industrial use**, can quickly and accurately provide ultra-thin film stack information. These three tools, based on the same technique, exhibit different ways to implement it, whether it is resolution driven or used in a production purpose.

XPS Configuration Comparison



How can the three different XPS configurations be compared ?

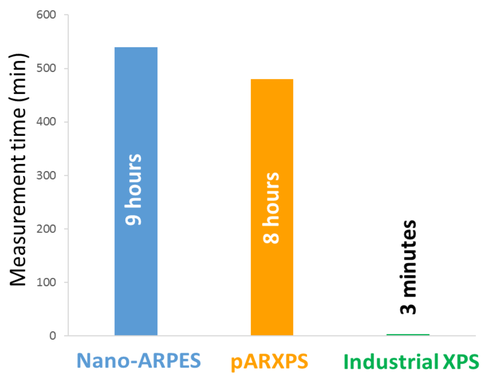


Comparison of Hf4f, Si2p and N1s XPS spectra obtained by Nano–ARPES, pARXPS and industrial XPS on the HfON/SiON/Si industrial gate stack.

Spin-orbit coupling of **Hf4f spectra** well resolved by **Nano-ARPES** and **pARXPS**. Less visible with the **industrial XPS**.

Smaller sampling depth with **Nano-ARPES** ➡ **Si2p spectra** presents a **smaller Si substrate peak.**

N1s spectra rather similar on 3 systems, except Si-N-O_2 peak which appears larger with **Nano-ARPES** and **pARXPS** (imputed to sample ageing).

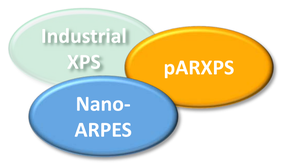


Time of acquisition per point of the three systems to obtain the different spectra of the HfON/SiON/Si sample.

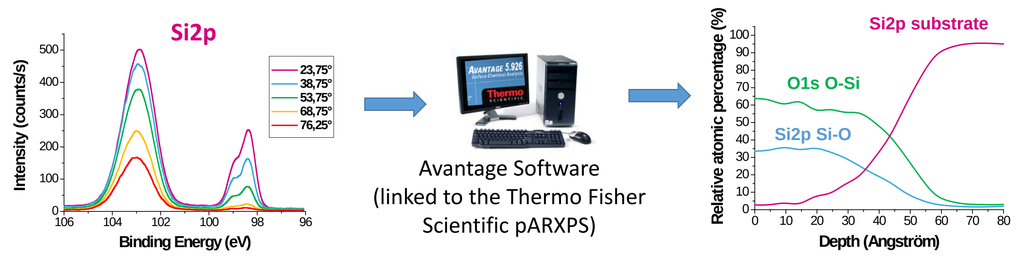
✓ **Nano-ARPES** has **the best resolution**, and **nearly similar resolution with pARXPS**: allow to resolve the different spin-orbit coupling.

✓ **Industrial XPS** shows **lower resolution**, nevertheless same peaks observed, and **time of acquisition tremendously reduced.**

XPS Chemical Profile Reconstruction

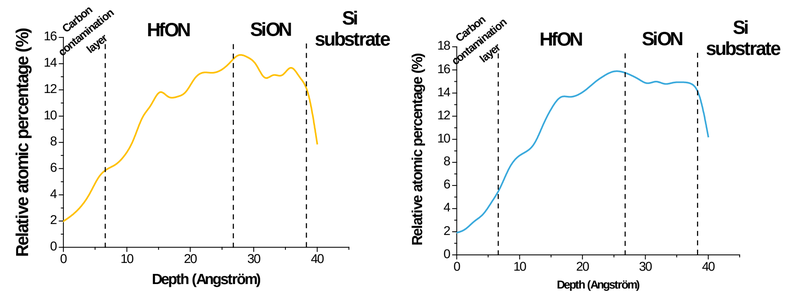


How to obtain the nitrogen chemical profile reconstruction based on Nano-ARPES and pARXPS angular information ?



Chemical profile reconstruction obtained by applying the maximum entropy concept to the angular information (Nano–ARPES and pARXPS).

Nitrogen chemical profile reconstruction of the HfON/SiON/Si sample, obtained with this technique, without applying any constrain or predefined model on calculations. Only the **six first angles have been used** (from **23.75°** to **61.25°**) to obtain chemical profile reconstruction, **elastic scattering phenomenon** becoming **predominant over 60°** [5].

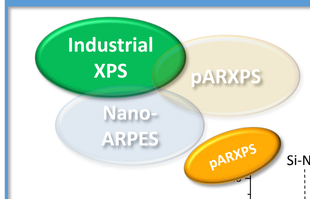


Nitrogen distributions obtained by chemical profile reconstruction with pARXPS spectra (left) and Nano–ARPES spectra (right).

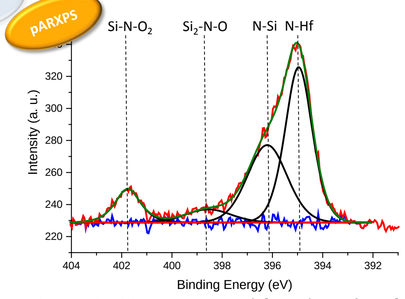
Nitrogen profiles nearly identical: increasing gradient in HfON layer and constant in SiON layer.

✓ Despite significant differences between **pARXPS** and **Nano-ARPES** (X-ray source, angular acquisition, …) **same nitrogen** profiles observed.

XPS For Industrial Control

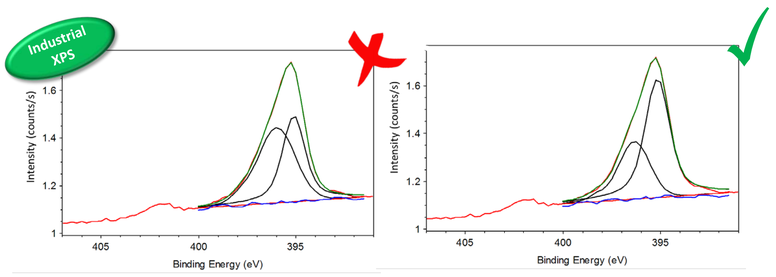


How Nano-ARPES and pARXPS analysis can help industrial control of the HKMG stack ?



N1s pARXPS spectra and fitted peaks of the HfON/SiON/Si stack obtained at 23.75°.

Thanks to **good pARXPS resolution** and **angular information**, different bonds contributions **accurately determined and fitted**.



N1s industrial XPS spectra, with a free fit (left) and a constrained fit based on the pARXPS and the Nano-ARPES measurements (right).

Free fit recipe of the N1s spectra

➡ **Wrong composition distribution**.

Constrains on the Full Width at Half Maximum (FWHM), based on the **pARXPS** and the **Nano-ARPES analysis**

➡ **Correct results**.

✓ Creation of **robust in-line XPS measurement program** on **industrial XPS** to measure simultaneously and independently **nitrogen amount** in **HfON layer** and **SiON layer.**

Conclusion

✓ **The measurement of same ultrathin HfON/SiON/Si stack on three different XPS configurations allowed us to highlight the differences of resolution and of acquisition time.**

✓ **The angular information obtained with a laboratory pARXPS and a Nano-ARPES using a SOLEIL synchrotron ANTARES beamline allowed to give access to an equivalent nitrogen profile in the HfON/SiON/Si stack.**

✓ **Based on Nano-ARPES and pARXPS analysis, a robust in-line XPS measurement program have been created on the industrial XPS, allowing us to simultaneously and independently measure the nitrogen amount in the HfON layer and in the SiON layer.**

References

[1] ITRS, “Roadmap for Semiconductors - Process Integration, Devices, and Structures," (2013).
[2] M. Cho, J. Park, H. B. Park, C. S. Hwang, J. Jeong, and K. S. Hyun, *Applied Physics Letters* **81,** 334 (2002).
[3] J. Avila, I. Razado, S. Lorcy, B. Lagarde, J.L. Giorgetta, F. Polack and M. C. Asensio, *Journal of Physics: Conference Series* **425** (2013).
[4] M. Py, J. P. Barnes, R. Boujamaa, M. Gros-Jean, K. Nakajima, K. Kimura, C. Roukoss, B. Pelissier and N. Gambacorti , *J. Vac. Sci. Technol.* pp.B 29 (2011).
[5] C. J. Powell, W. S. M. Werner and W. Smekal, *Surf. Interface Anal*. **43,** 1046 (2011).

This work has been partially supported by the French Government program “Investissements d’Avenir” managed by the National Research Agency (ANR) under the contract number ANR-10-EQPX-33.