Application Note

Metrology of 3D Transistors for La/Hf, Co, Ni dopant and thicknesses to sub-Angstrom equivalent thicknesses

By Dr. Benjamin Stripe, Xiaolin Yang, Sylvia Lewis | Sigray. Inc

Abstract

We describe a new technique for non-destructive, quantitative measurements of next-generation transistors, such as FinFETs and Gate All Around (GAA) transistors. The Sigray AttoMap XRF microscope achieves ultrahigh sensitivity that is equivalent to sub-1 Angstrom measurements in spot sizes below 10 µm, which matches the needs of shrinking test pads. This approach provides ultra-high sensitivity at high throughput down to seconds for critical dopants and thin film elements such as La, Hf, Ni, Co, and has demonstrated <1% repeatability for 1-2 nm thicknesses measured within 2 minutes.

Introduction

Fast, non-destructive, and quantitative composi-tional analysis of trace level dopants and nano-structures is a major capability demand among the semiconductor and nanotechnology research community. The need for such analysis is driv-en by the rapid growth of 3D (non-planar) tran-sistors such as finFETs and new nanowire-based gate-all-around (GAA) structures. These 3D new geometries, dimensions, and compositions intro-duce major challenges for reliable quantitative re-sults using existing measurement approaches1-2. Furthermore, these systems must achieve the required high perfor-mance on smaller test struc-tures (e.g. 50 µm pads) of transistor arrays.

Current approaches: Nano-SIMS and TEM

Secondary Ion Mass (SIMS) spectrometry has been the workhorse analytical technique, in which a focused ion beam sputters the surface of a spec-imen, forming sec-ondary ions that are analyzed for composition. However, 3D transistors intro-duce substantial challenges in its use, including quantification inaccuracies because of sputtering rate variations, which can be due to factors such as non-planar structures1 and impurities in high-k gate hafnium dielectrics3. In addition, the acquisi-tion times required for accurate analysis is a bot-tleneck, typically taking ~30 minutes per test pad point.

To address these problems, Transmission elec-tron mi-croscopy (TEM) is used. TEM measures the transmission of electrons through a sample, and as a result, requires the preparation of an ultrathin lamella of <100 nm for a region-of-interest. TEM is labor-intensive and very low throughput, and the sample preparation and region-of-interest can re-move or destroy features of interest.

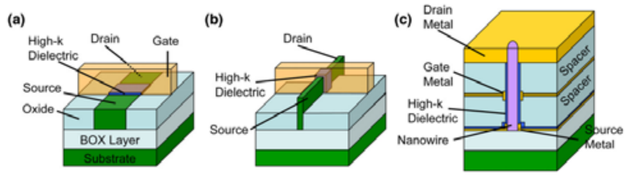

Figure 1. Semiconductor MOSFET designs: traditional 2D planar designs (shown in a) are now moving to complex 3D structures in 3D FinFETs (b) and proposed vertical nanowire designs (c), resulting in new analytical chal-lenges. A Moore and L Shi, "Emerging challenges and materials for thermal management of electronics." Materials Today 2014

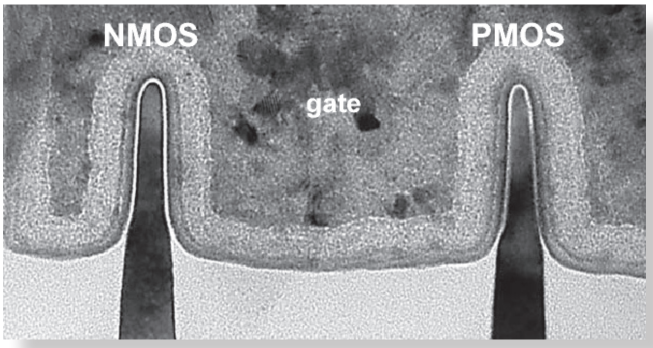

Figure 2. Current approaches to measure thin films are SIMS or TEM sectioning, both which are low-throughput and destructive. Shown above is a TEM image of a 16-nm finFET. D James, "Moore's Law Continues into the 1x-nm Era." 21st Itnl Conference on Ion Implanation Technology 2016.

A novel approach: Sigray AttoMap XRF Microscope

Sigray, through patented breakthroughs in x-ray source and x-ray optic technologies, has developed the AttoMap XRF microscope with sub-femtogram sensitivities in a 10 µm spot. This technique has now been installed by two of the largest IDMs (integrated device manufacturers). With the AttoMap, relative concentration can be provided with a high degree of accuracy without standards, and absolute concentration of high-k dielectrics of 1-2 nm thicknesses have been measured within 2 minutes with 1% repeatability.

Metrology of 3D Transistors for La/Hf, Co, Ni dopant and thicknesses to sub-Angstrom equivalent thicknesses

Application Note

By Dr. Benjamin Stripe, Xiaolin Yang, Sylvia Lewis | Sigray. Inc

Unlike other techniques, x-ray quantification is not impacted by the 3D nature of finFET and nanowire transistors. Moreover, the AttoMap is non-destructive, making it ideal as a complementary upstream technique to SIMS and TEM for identifying regions of interest.

Experiment summary

The AttoMap was used on third party prepared samples of thin films on Si substrates to validate its capabilities and to measure its lower limit of detection (LLD). Its multi-target x-ray source enabled the selection of different x-ray targets to optimize the x-ray fluorescence signal for different thin films of interest. This capability is unique to the AttoMap and, as can be seen from Table 1 for Co, enables optimal lower limits of detection (LLDs).

Moreover, quantitative linearity was established with thin films (e.g. Ni, Co, HfO) of varying thicknesses: 5, 10, and 20 Angstroms. The AttoMap, using a special x-ray source target unique to Sigray, has also demonstrated powerful capabilities for sub-angstrom measurements of high-k dielectrics (Hf and La) for process inspection.

Summary

Sigray's AttoMap provides a non-destructive, ultra-high sensitivity approach for 3D transistors, which has led to its rapid adoption by advanced semi-conductor manufacturing. Its patented high brightness x-ray source and x-ray optics enable excellent throughput and sensitivity, and moreover, due to its multi-target x-ray source design, the system has optimal performance for most elements-of-interest. The system can be used for monitoring Hf/La ratios, thickness of Co interconnects, or Ni mask residues.

Thin film	Source target	Lower limit of detection with 99.7% confidence
Co	Moly (k-a: 17.4 keV)	0.27 Angstroms
Co	Copper (k-a:8 keV)	0.03 Angstroms
Ni	Moly (k-a: 17.4 keV)	0.31 Angstroms

Table 1. Lower limits of detection with 3-sigma confidence at 400s: LDLs of well below sub-angstrom can be obtained with Sigray's AttoMap non-destructively. Moreover, as can be seen from the Co thin film rows, choice of x-ray source target matters: Cu has a ~10X better LDL than a Mo target. This is why AttoMap uses a patented multi-target x-ray source.

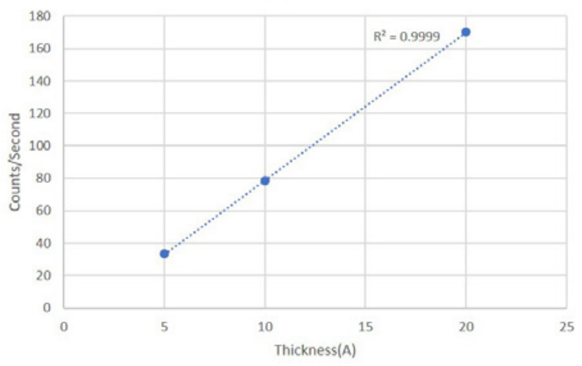
Spectra of 5 Angstrom Co film with peak fitting
Co thickness (in Angstroms) vs counts/second

Figure 3. Co thickness linearity: Linearity of 5, 10, and 20 Angstrom Co films showing a r^2 linear regression of 0.9999. Counts/s shown are at a "flat" geometry; a 20X increase in counts/s can be achieved at higher angles.
* The system provides excellent results for Hf and La, but due to NDA, these results cannot be shown in this applications note. Contact Sigray for running such samples.

References

1. AA Budrevich and W Vandervost. "Chapter 5: SIMS Analysis on the Transistor Scale: Probing Composition and Dopants in Nonplanar, Confined 3D Volumes," Metrology and Diagnostic Techniques for Nanoelectronics. Eds: Z Ma and DG Seiler (2017) Pan Stanford Publishing Pte. Ltd.
2. J Bennett, et al. "SIMS depth profiling of advanced gate dielectric materials," Applied Surface Science 203 (2003).
3. T Hasegawa, S Akahori. "High reliable quantification analysis of impurities in high-k gate dielectrics by SIMS," Special Issue on the Depth Profiling of Ultra Thin Films 28:11 (2007): 638-641.