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# Advanced characterization for copper interconnect technology

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## ABSTRACT

Advanced interconnect integration for 45-nm nodes and below requires the use of copper metal lines and ultra low- $k$  materials in order to control the delay, the crosstalk and the power consumption of the integrated circuits. This induces architecture specifications with introduction of new materials and new processes. Advanced physical and chemical characterization is mandatory to support not only the material choice and its improvement, the analysis of scaling effects and their correction, but also the design of integration processes and their validation. This article gives an overview of the most challenging characterization techniques in terms of their capabilities and limitations, giving special attention to sensitivity, localization and in-line metrology issues.

## Challenges of advanced interconnect integration

As indicated by the 2004 update of the ITRS [1] for the 45nm nodes and below, the use of copper-based metal lines and ultralow- $k$  (ULK) dielectrics in the back end of the line (BEOL) integration processes is mandatory for the delay, the cross talk and the power consumption control in the new generation of integrated circuits. The integration of copper and ultralow- $k$  materials induces architecture limitations related to the introduction of diffusion metal barriers, dielectric-wall densification, hard masks, etch stop layers and dielectric barriers. Indeed, after integration, the metal line effective resistivity is higher than the copper one and the dielectric effective  $k$  value is higher than the ultra low- $k$  material one. Limiting this effect requires the use of layers as thinnest as possible (<5 nm) and to reduce their number avoiding the etch stop layer for example.

Furthermore, the metal line width is scaling down as the metal 1 pitch to be used is of about 100 nm and below. Then the copper resistivity is governed not only by the chemical contamination and

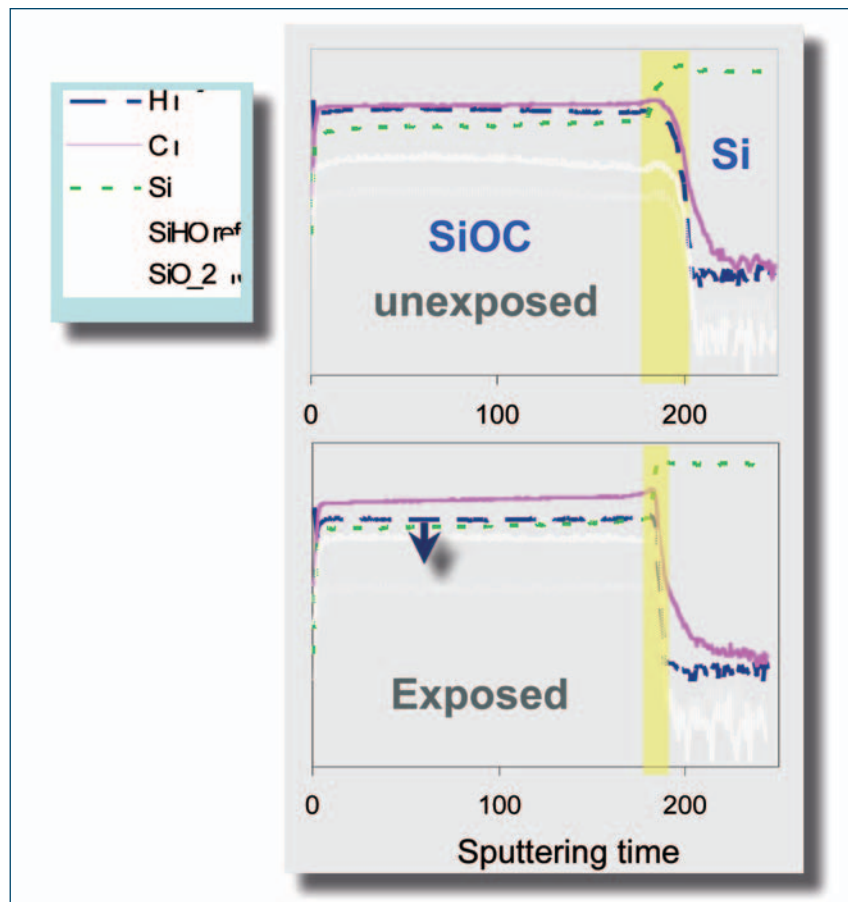


Figure 1. TOF-SIMS profiles in a silicon oxycarbide layer ( $\text{SiO}_x\text{C}_y$ ) on silicon substrate obtained with charge neutralization using a low-energy electron bombardment on two areas of the sample after magnetic SIMS analysis: Top graph, sample area unexposed; Bottom graph, exposed area to a high-energy electron bombardment during magnetic SIMS analysis. The layer composition modification (H content decrease) and the interface thinning are induced by the exposure to the high-energy electron beam.

electron reflection at grain boundaries but also by the electron scattering at surfaces. The only way to control the Cu line resistivity increase with the line width scaling down is to maximize the Cu grain size and minimize the sidewall roughness of the lines.

As a result, new materials and new integration processes are under investigation in order to meet these requirements. Some of the issues are given below:

- The metal barrier efficiency at the lowest thickness possible with regards to the Cu diffusion into the dielectric material,
- The dielectric barriers and hard mask chemical and mechanical stability at the lowest thickness possible and with a  $k$  value as low as possible,

- The integrity of the ultralow- $k$  material during integration processes with regards to their mechanical properties and metal diffusion from the surrounding barriers.
- The control of the metal grain size during deposition and integration processes and grain-orientation effect on other material integration.

Then, the role of the physical and chemical characterization is to support not only the material choice and its improvement, the analysis of scaling effects and their correction, but also the design of integration processes and their validation. In Table 1, the most important information expected from the different fields of characterization is summarized. Below, we will highlight the challenges of the most useful

TABLE 1: RELEVANT INFORMATION VS PHYSICAL AND CHEMICAL CHARACTERIZATION FIELDS

Characterization field	Information expected	Techniques
Chemical	• Composition	RBS, MEIS, NRA, ERDA, SIMS, AES, XRF, NMR
	• Surface chemistry • Contamination	XPS, ATR, MIR, IR-SNOM, AAS, ICPMS, XRF
	• Inter material diffusion	SIMS, RBS, MEIS, AEM, AES, ICPMS, AAS
Morphological	• Roughness	2D & 3D AFM, XRR, Scatterometry
	• Thickness • Layer continuity • Pattern geometry	SEM, TEM, 3D AFM, XRR, SE, PAW, TOFSIMS
	• Material density • Pore size: mean value & distribution • Pore sealing	EP, PALS, GISAXS, TEM Tomography
	Mechanical	• Young modulus • Hardness
• Stress		XRD, Curvature
• Adhesion energy		4 point bending, Bulge test, Nanoindentation
Thermal	• Thermal expansion coefficient • Thermal stability	SE, XRR, PAW, Curvature
Structural	• Grain size • Texture	XRD, EBSD, TEM, AFM, FIB
	• Crystalline phase	XRD, TEM
	Electrical	• Resistivity
• Dielectric constant		Hg-probe, Corona effect

AAS: Atomic Absorption Spectroscopy	MIR: FTIR Multiple Internal Reflection	RBS: Rutherford Back Scattering
AEM: Analytical Electron Microscopy	GISAXS: Grazing Incidence Small Angle X-ray Scattering	SAW: Surface Acoustic Waves
AES: Auger Electron Spectroscopy	ICPMS: Ion Coupled Plasma Mass Spectroscopy	SE: Spectroscopic Ellipsometry
AFM: Atomic Force Microscopy	IR-SNOM: Infra Red Scanning Near field Optical Microscopy	SEM: Scanning Electron Microscopy
ATR: FTIR Attenuated Total Reflection	MEIS: Medium Energy Ion Scattering	SIMS: Secondary Ion Mass Spectroscopy
BLS: Brillouin Light Scattering	MIR: FTIR Multiple Internal Reflection	TEM: Transmission Electron Microscopy
DSC: Differential Scanning Calorimetry	NMR: Nuclear Magnetic Resonance	TDA: Thermal Desorption analysis
EBSD: Electron BackScatter Diffraction	NRA: Nuclear Reaction Analysis	TGA: Thermal Gravimetry
EDS: Electron Dispersive X-ray Spectroscopy	PALS: Positron Annihilation Lifetime Spectroscopy	TOFSIMS: Time Of Flight SIMS
EELS: Electron Energy Loss Spectroscopy	PAW: Photo-Acoustic Waves	XPS: X-ray Photoelectron Spectroscopy
EP: Ellipsometric Porosimetry		XRD: X-Ray Diffraction
ERDA: Elastic Recoil Detection Analysis		XRF: X-Ray Fluorescence
FIB: Focused Ion Beam		XRR: X-Ray Reflectometry

characterization techniques to obtain the relevant information. The electrical measurements are kept out of the scope of this article.

### Chemical analysis

The state-of-the-art in chemical analysis is summarized in Table 2 in terms of capabilities and limitations of the most challenging techniques. Bold characters highlight the particularly relevant items for the Cu interconnects integration. The main tool improvements expected with regards to the present limitations are mentioned. As indicated in Table 2, three types of chemical analysis must be distinguished that are required to support Cu, barriers, ULK developments and their integration.

Depth profiling deals with the new materials composition and their

compatibility since diffusion between layers in stacks may occur, for example. This is usually performed by SIMS [2] and RBS [3]. SIMS suffers from the sensitivity to charge effects when dielectric materials are concerned. Usually, charge neutralization is obtained through electron bombardment of the sample surface. In the magnetic SIMS configuration, the electron energy is of a few keV, inducing a material damage [4] incompatible with an accurate analysis (Figure 1). Due to its sequential operation, dual-beam TOF-SIMS allows charge neutralization with a grounded sample. As a consequence, the electron energy may be as low as 20 eV, which would avoid ULK material modification during analysis. The most important interest for the BEOL is the specifically high sensitivity to heavy elements

(Figure 2) of RBS and its compatibility with dielectric materials since no charges are deposited in the sample. It is limited by the low depth resolution but improvements are expected from the energy decrease of the probe particles in the MEIS configuration [5].

Surface chemical analysis is required for example to control the ULK compatibility with chemistries during the cleaning processes (Figure 3) and the surface treatments like ULK pore sealing and barrier improvements in order to avoid metal diffusion [6]. Indeed, ATR [7] and MIR [8] optical configurations of FTIR spectrophotometry and XPS-UPS show real capabilities in that field but they have a poor spatial resolution with regards to the need for spatial inhomogeneity control and to emerging processes like local deposition of self-

TABLE 2: STATE OF THE ART IN CHEMICAL ANALYSIS AND TOOL IMPROVEMENTS EXPECTED

Type	Technique	Capabilities	Limitations	Improvements						
Depth profiling	SIMS <i>Ion sputtering</i>	<ul style="list-style-type: none"> <li>• Majors, minors, traces and isotopes with high dynamic range</li> <li>• <b>High depth resolution: &lt;1nm</b></li> <li>• Quantitative</li> </ul>	<ul style="list-style-type: none"> <li>• UHV</li> <li>• Destructive</li> <li>• <b>Low spatial resolution</b></li> <li>• <b>Charging effects</b></li> </ul>	<b>TOF-SIMS</b> <ul style="list-style-type: none"> <li>• <i>Sequential operation</i></li> <li>• <i>Liquid source</i></li> </ul>						
	RBS <i>Ion sputtering</i>	<ul style="list-style-type: none"> <li>• Heavy elements</li> <li>• Light elements by NRA</li> <li>• Quantitative</li> </ul>	<ul style="list-style-type: none"> <li>• Limited depth resolution</li> <li>• <b>Limited sensitivity</b></li> <li>• Low spatial resolution</li> <li>• Time consuming</li> </ul>	<b>MEIS</b> <i>Particle lower energy</i>						
Surface analysis	XPS-UPS <i>Photoelectron emission</i>	<ul style="list-style-type: none"> <li>• <b>Bonding states in ultra thin films &lt;10nm</b></li> <li>• Almost quantitative</li> <li>• Cluster tool compatible</li> <li>• Non destructive</li> </ul>	<ul style="list-style-type: none"> <li>• UHV</li> <li>• <b>Embedded interfaces</b></li> <li>• <b>Low spatial resolution</b></li> <li>• Charging effects</li> <li>• Time consuming</li> </ul>	<ul style="list-style-type: none"> <li>• <b>PEEM</b> <i>Imaging</i></li> <li>• <b>Synchrotron PS</b> <ul style="list-style-type: none"> <li>• <i>Energy tunability</i></li> <li>• <i>High brightness</i></li> </ul> </li> </ul>						
	FTIR <i>IR light absorption</i>	<table border="1"> <tr> <td>MIR</td> <td rowspan="2"> <ul style="list-style-type: none"> <li>• <b>Bonding states in ultra thin films and interfaces</b></li> <li>• Almost quantitative</li> <li>• Room atmosphere</li> </ul> </td> </tr> <tr> <td>ATR</td> </tr> </table>	MIR	<ul style="list-style-type: none"> <li>• <b>Bonding states in ultra thin films and interfaces</b></li> <li>• Almost quantitative</li> <li>• Room atmosphere</li> </ul>	ATR	<table border="1"> <tr> <td>MIR</td> <td rowspan="2"> <ul style="list-style-type: none"> <li>• High resistivity and double side polished Si substrate</li> <li>• <b>No spatial resolution</b></li> <li>• <b>With contact</b></li> </ul> </td> </tr> <tr> <td>ATR</td> <td> <ul style="list-style-type: none"> <li>• High refractive index substrate</li> <li>• <b>Low spatial resolution</b></li> <li>• <b>With contact</b></li> </ul> </td> </tr> </table>	MIR	<ul style="list-style-type: none"> <li>• High resistivity and double side polished Si substrate</li> <li>• <b>No spatial resolution</b></li> <li>• <b>With contact</b></li> </ul>	ATR	<ul style="list-style-type: none"> <li>• High refractive index substrate</li> <li>• <b>Low spatial resolution</b></li> <li>• <b>With contact</b></li> </ul>
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Pattern analysis	TEM <i>Electron transmission</i>	AEM	<ul style="list-style-type: none"> <li>• Element map</li> <li>• <b>Spatial resolution 2nm</b></li> </ul>	<ul style="list-style-type: none"> <li>• Low sensitivity</li> <li>• <b>Destructive</b></li> <li>• Time consuming</li> </ul>	<ul style="list-style-type: none"> <li>• <b>FIB sampling on full wafer</b></li> <li>• <b>Column aberration correction</b></li> </ul>					

aligned barriers. Further improvements in IR spectrophotometry will become, through the development of near-field configurations, combined with synchrotron radiation [9]. XPS improvements in surface sensitivity and chemical selectivity have been demonstrated through the use of synchrotron radiation thanks to its high brightness and energy tunability [10]. In the same way, a significant rise in spatial resolution is also expected allowing imaging as illustrated in Figure 4.

Pattern chemical analysis is mainly required for metal diffusion control into the ULK material during integration processes [11]. AEM gives access to the spatial distribution of chemical elements in patterned samples. Since it is performed in a TEM tool, a high spatial resolution may be achieved. An extensive use is expected through the development of FIB sampling on a full wafer. However, it still suffers from a poor sensitivity that should be improved by the development of an aberration-corrected TEM column.

### Structural analysis

The state-of-the-art in structural analysis from the point of view of BEOL issues concerns three diffraction techniques: XRD, EBSD and TEM. They are used to support metal line developments dealing with the polycrystalline properties and strain control. These three techniques give the crystallographic axes with respect to the sample reference axes (Figure 5) but they have different capabilities and limitations as reported in Table 3. The limitations that stand out are the

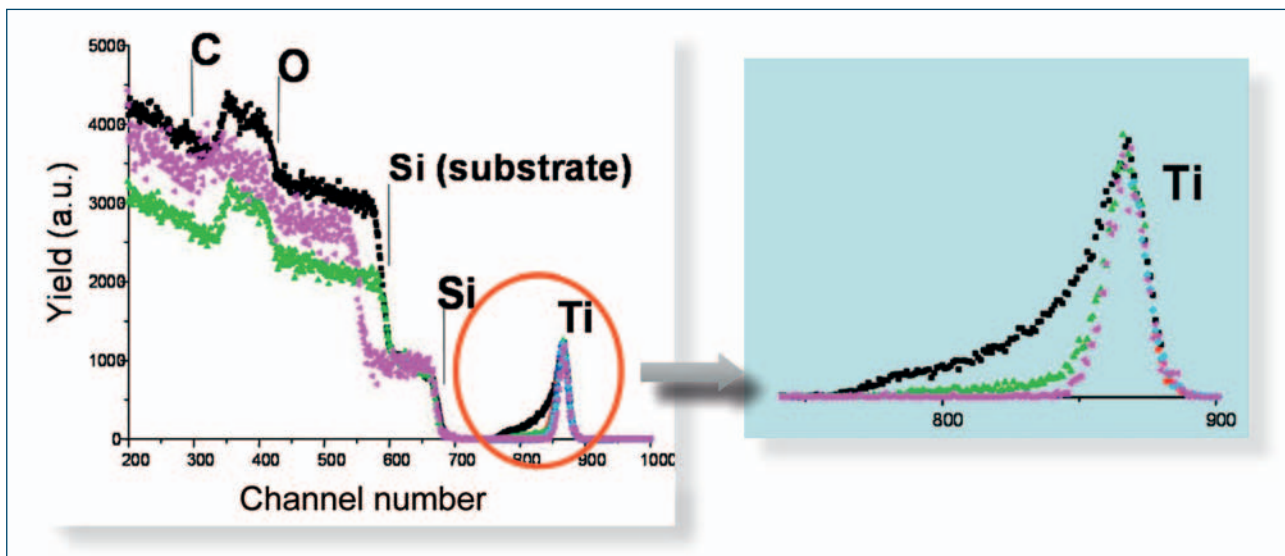


Figure 2. RBS spectra obtained on TiN barrier (10 nm)/dielectric layer (~300 nm)/Si substrate stacks: Violet dots, SiO<sub>2</sub> dielectric layer; Black dots, porous SiO<sub>x</sub>C<sub>y</sub> dielectric layer; Green dots, porous SiO<sub>x</sub>C<sub>y</sub> with surface pore-sealing treatment before TiN deposition. RBS analysis is used to check how the pore-sealing treatment prevents Ti diffusion into the porous material by comparison to the dense SiO<sub>2</sub> material.

TABLE 3: STATE OF THE ART IN STRUCTURAL ANALYSIS BY DIFFRACTION TECHNIQUES AND TOOL IMPROVEMENTS EXPECTED

Capabilities & limitations	XRD Reflected X-Rays	EBSD Back scattered electrons	TEM Transmitted electrons
Penetration depth	Few $\mu\text{m}$	<b>Few 10nm</b> (FIB cuts)	Transmission (slice)
Spatial resolution	100 $\mu\text{m}$	Few 10nm	<b>~1nm</b>
Field of view	Several $\text{mm}^2$	Several 10 $\mu\text{m}^2$	Few $\mu\text{m}^2$
Grain orientation	<b>Average on multiple lines</b>	<b>Map, individual grain</b>	<b>Map, individual grain</b>
Twin and grain boundaries	No	<b>Yes</b>	Yes
Texture	<b>High angular resolution</b>	Low angular resolution	Local
Phase	Yes	No	Yes
Strain	<b>Averaged on multiple grains</b>	No	No
Sample	<b>No restrictions</b>	<b>Capping layers incompatible</b>	Thinned <100nm
Metal structures	Array of metal lines	Individual lines or array	<b>Individual lines, Seed layers, Diffusion barriers</b>
In-line	<b>Non destructive (test arrays)</b>	<b>Plane view non destructive</b>	<b>FIB sampling on full wafer</b>
Improvements	Synchrotron radiation	Sequential FIB cuts: 3D	Higher automation of TEM

average information in XRD, the surface information in EBSD and the time-consuming sample preparation in TEM. Among the improvements expected (Table 3), the use of the synchrotron radiation in XRD have to be pointed out. Tamura et al. [12] have shown that grain-orientation mapping may be achieved at the grain size scale using a synchrotron white beam then strain and strain mapping is extracted from monochromatic beam use. Spot size improvements are still ongoing in order better to meet the BEOL requirements.

### Morphological analysis

Table 4 gives a general overview of the state-of-the-art in morphological analysis that may be separated into four different domains: pattern morphology, critical dimensions (CD) and roughness, thickness and density then porosity. The techniques taken into account for each

domain are the most widely used ones.

Pattern morphology required for process integration control is currently achieved by SEM due to the relatively high speed of the observations. Within the 45nm node and below, the dimension scaling down requires increasing electron energy in order to improve the spatial resolution. Unfortunately, the ULK materials degrade under electron irradiation. With the help of a higher automation inducing a higher throughput, TEM is expected to be the only way to eliminate that SEM issue. Indeed, in a thinned sample, such as a TEM one, the deposited energy is very low, which maintains the ULK material integrity.

As metal line width scales down, top view CD SEM [13] and 3D AFM [14] shows great capabilities for CD measurements but only 3D AFM is able to separate between CD and line edge

roughness by changing the scan rate. However (Figure 6), the development of the 3D AFM use is highly limited by the AFM tip lifetime. Improvements are expected from the use of carbon nanotube tips.

In Cu interconnects, ellipsometry, the most used technique for thickness measurements does not apply to stacks of metal films. In that case, only XRR is appropriate and gives full results in terms of thickness and density of each layer of the stack [15]. However, it shows a severe limitation due to its foot print on the sample related to the grazing incidence operation.

Both ellipsometry [16] and XRR [17] can be coupled with gas adsorption giving access to complete information about ULK porosity. However, their use would be limited due to their intrusive nature. GI-SAXS should be a good candidate as a nonintrusive

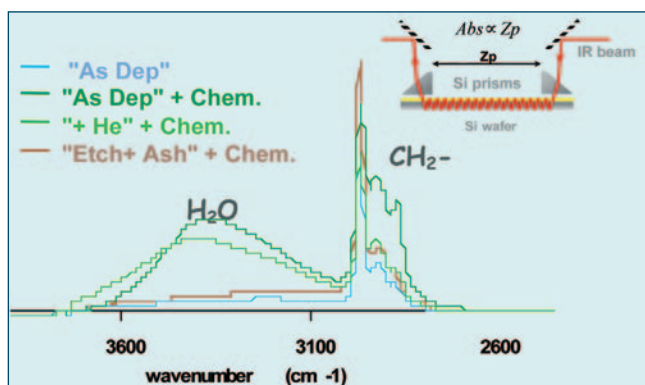


Figure 3. MIR-FTIR spectra obtained on an ULK layer deposited on double-side polished silicon wafer with high resistivity (inset: MIR configuration scheme). The MIR analysis high surface sensitivity allowed to study water adsorption ( $\text{H}_2\text{O}$  absorption band) and surfactant adsorption ( $\text{CH}_2$ - absorption band) at ULK material surface after a chemical cleaning process.

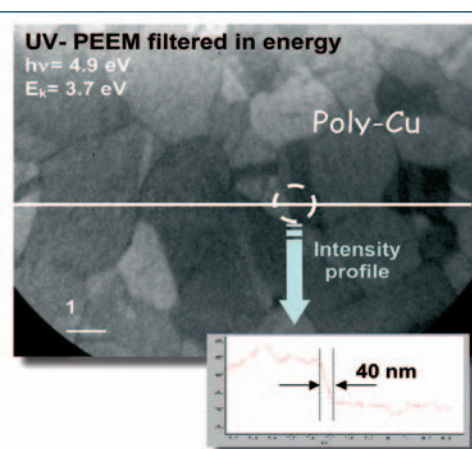


Figure 4. Synchrotron UV-PEEM filtered in energy obtained from a polycrystalline Cu surface showing emission contrast related to the variation of the Cu work function with the grain orientation with a high spatial resolution.

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TABLE 4: STATE OF THE ART IN MORPHOLOGICAL ANALYSIS AND TOOL IMPROVEMENTS EXPECTED

Type	Technique	Capabilities	Limitations	Improvements
Pattern morphology	SEM <i>Cross section electron emission</i>	<ul style="list-style-type: none"> <li>• Localization</li> <li>• Rapid</li> </ul>	<ul style="list-style-type: none"> <li>• High power deposition</li> </ul>	TEM
	TEM <i>Thinned sample electron transmission</i>	<ul style="list-style-type: none"> <li>• Localization</li> <li>• High resolution</li> <li>• Low power deposition</li> </ul>	<ul style="list-style-type: none"> <li>• Destructive</li> <li>• Time consuming</li> </ul>	<ul style="list-style-type: none"> <li>• FIB sampling on full wafer</li> <li>• Higher automation</li> </ul>
CD and Roughness	Top view CD SEM <i>Top surface electron emission</i>	<ul style="list-style-type: none"> <li>• In-line metrology</li> </ul>	<ul style="list-style-type: none"> <li>• Image reconstruction</li> </ul>	Image reconstruction software
	3D AFM <i>Tip-surface interaction</i>	<ul style="list-style-type: none"> <li>• Direct 3D imaging of 2D structures</li> <li>• CD and edge roughness</li> <li>• In-line compatible</li> </ul>	<ul style="list-style-type: none"> <li>• Tip curvature and life time</li> </ul>	Carbon nanotube tip <i>High aspect ratio</i>
Thickness and density	SE <i>Light polarization</i>	<ul style="list-style-type: none"> <li>• Dielectric function and thickness</li> <li>• Non destructive, non intrusive</li> <li>• In-line &amp; In-situ metrology</li> </ul>	<ul style="list-style-type: none"> <li>• Model parameter correlation</li> <li>• Thickness only for transparent layers</li> <li>• Limited spatial resolution</li> </ul>	Sample heating <i>Temperature variation</i>
	XRR <i>X-ray reflection</i>	<ul style="list-style-type: none"> <li>• Thickness and electron density profile</li> <li>• No correlation</li> <li>• In-line &amp; In-situ metrology</li> </ul>	<ul style="list-style-type: none"> <li>• Thickness limited to 2-200nm range</li> <li>• Large spot foot print</li> </ul>	
Porosity	EP <i>SE with gas adsorption</i>	<ul style="list-style-type: none"> <li>• Pore size and distribution</li> <li>• Young modulus</li> </ul>	<ul style="list-style-type: none"> <li>• Model parameter correlation</li> <li>• Intrusive and time consuming</li> </ul>	<ul style="list-style-type: none"> <li>• Model development</li> <li>• Commercial tools (under test)</li> </ul>
	GI-SAXS <i>X-ray reflection</i>	<ul style="list-style-type: none"> <li>• Pore size and distribution</li> <li>• Non destructive, non intrusive</li> </ul>	<ul style="list-style-type: none"> <li>• Still qualitative</li> <li>• Large spot foot print</li> </ul>	

TABLE 5: STATE OF THE ART IN MECHANICAL ANALYSIS AND TOOL IMPROVEMENTS EXPECTED

Type	Technique	Capabilities	Limitations	Improvements
Mechanical properties	Manoindentation <i>Indentation area</i>	<ul style="list-style-type: none"> <li>• Film hardness &amp; Young modulus</li> <li>• High spatial resolution</li> <li>• Rapid</li> </ul>	<ul style="list-style-type: none"> <li>• Required inputs: Poisson coefficient (BLS)</li> <li>• Locally destructive</li> </ul>	Indenter optimization <i>Measurement reliability</i>
	SAW <i>Wave velocity</i>	<ul style="list-style-type: none"> <li>• Film Young modulus</li> <li>• Rapid</li> <li>• Non destructive, non invasive</li> </ul>	<ul style="list-style-type: none"> <li>• Blanket films</li> <li>• Model parameter correlation</li> <li>• Required inputs: density (XRR), Poisson coefficient (BLS), thickness (ES, XRR)</li> </ul>	<ul style="list-style-type: none"> <li>• Optical detection</li> <li>• Spatial resolution</li> </ul>
Mechanical behaviour	Four point bending <i>Crack propagation</i>	<ul style="list-style-type: none"> <li>• Stack adhesion energy</li> <li>• Crack propagation rate</li> <li>• Compatible with patterned structures</li> <li>• Commercial tool available</li> </ul>	<ul style="list-style-type: none"> <li>• Specific sample preparation</li> <li>• Poor notch manufacturing repeatability</li> <li>• Need post chemical analysis for crack interface identification</li> <li>• Destructive</li> </ul>	<ul style="list-style-type: none"> <li>• Sample preparation reliability</li> <li>• Environment control</li> <li>• Chemical dependence</li> </ul>

technique (Figure 7) but it suffers from poor development of the data analysis, which means the information is only qualitative.

## Mechanical analysis

This last type of characterization arises in the BEOL with the introduction of ULK materials. The porous nature of these materials induces several issues related to their poor mechanical properties: shrinking during integration

process steps, delaminating during CMP, device failure after packaging. As a result, the mechanical properties and the mechanical behavior of these materials must be controlled throughout the whole integration process taking into account that they may be affected by the thermal budget and the chemical treatments. For that purpose, different characterization techniques (Table 5) are under test and development for the application to ULK based structures.

Nanoindentation is the most widely used technique for extraction of film hardness and Young's modulus after curvature measurements thanks to the local information that may be achieved. Nevertheless, issues related to the measurement reliability are faced since interference from substrate effects may occur as the film thickness is reduced. Improvement has been demonstrated by the use of optimized indenters that are not yet readily available [18]. As

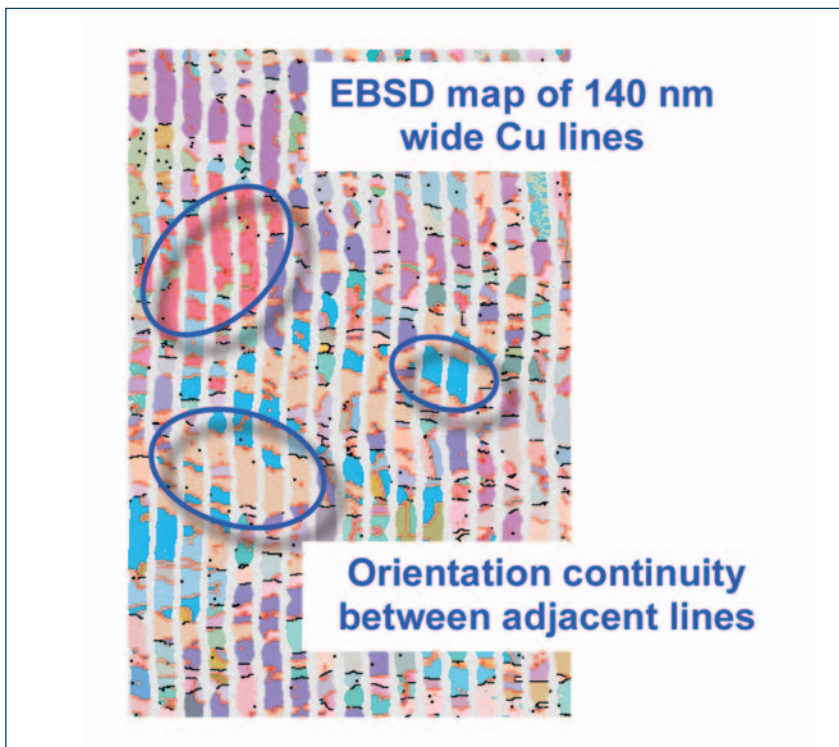


Figure 5. EBSD map obtained on Cu line series. Each color corresponds to a given grain orientation at the top surface of the layer. The orientation continuity between adjacent lines is due to the post-annealing CMP indicating that grain growth starts from the Cu layer top surface.

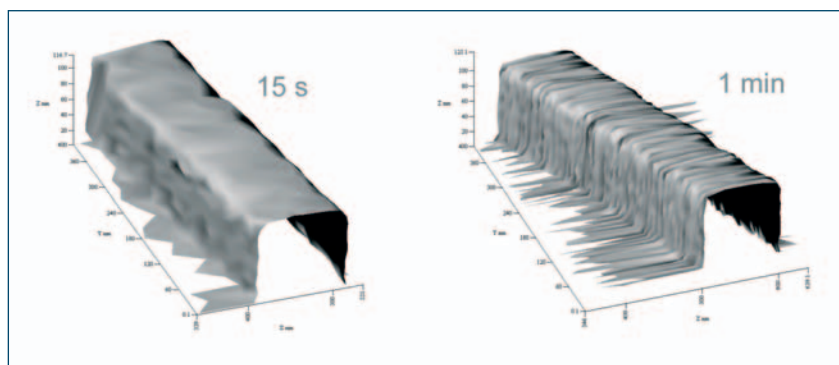


Figure 6. 3D AFM maps obtained on dielectric lines at different scanning rates: Left, high scanning rate for CD measurement; Right, low scanning rate for roughness measurement.

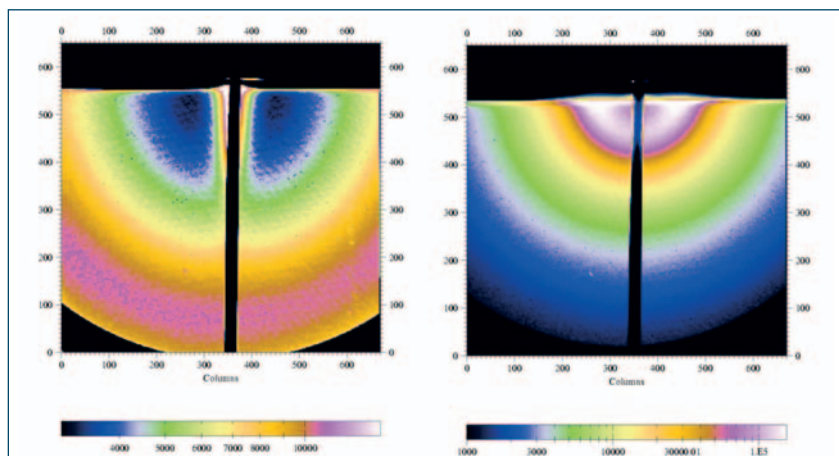


Figure 7. GI-SAXS color maps obtained from porous dielectric materials: Left, PECVD deposition (interpore distance: ~ 2 nm, pores diameter: ~ 1 nm); Right, spin-coating deposition (interpore distance: ~ 10 nm, pores diameter: ~ 4–5 nm). A qualitative interpretation is possible through comparison between different materials.

a complementary technique, SAW shows potential capabilities due its nondestructive nature [19] if assisted by other techniques as mentioned in Table 5. To eliminate the poor spatial resolution that limits the use to blanket films, developments of optical-detection-based tools [20] are under test.

Film-adhesion properties may be efficiently analysed by the four-point bending configuration as illustrated by the work of Dauskardt et al. [21]. Since this technique requires specific sample processing and preparation, it is not expected to be used as an in-line tool. Nevertheless, it stands up as the most powerful technique to support ULK material choice and integration. In addition to stack adhesion energy measurement, chemical dependence of the crack propagation rate would be allowed by the development of tools with environment control in order to control the stack mechanical behavior during chemical-mechanical polishing process steps.

## Conclusion

As a result of this brief overview, the challenges of the advanced physical and chemical characterization techniques for the BEOL issues of the 45nm nodes and below address the improvement of existing techniques, the development of innovative techniques and the in-line metrology needs that are highest automation, full-wafer capabilities, high throughput and wafer mapping. A lot of the challenging techniques have in-line capabilities as summarized in Table 6. Moreover, those that are not directly compatible because of their destructive nature for example, may be very useful as at-line techniques.

Finally, the main roads of developments that advanced microelectronic technologies are waiting for, may be summarized within three requirements:

- The sensitivity enhancement: the sampling development and source and detector improvement have been already conducted; now, a lot is expected from synchrotron radiation use.
- The compatibility with patterned wafers: this has been circumvented through simulation of process steps on full-wafer films and use of focused beams; today, improvements are expected with the help of scanning probe microscopy.
- The compatibility with in-line metrology of destructive techniques: generally, sacrificial wafers are used or mask test areas are defined; the cost

TABLE 6: IN-LINE CAPABILITIES VS PHYSICAL AND CHEMICAL CHARACTERIZATION FIELDS

	Technique	Challenges	Metrology
<b>Chemical analysis</b>	Mass spectroscopy	Neutralization Spatial resolution	At line
	Ion scattering	Depth resolution	Off line
	IR spectroscopy	Spatial resolution	In line
	Photoelectron spectroscopy	Spatial resolution	In line
	Electron energy loss spectroscopy	Spatial resolution TEM column stability	At line
<b>Structural analysis</b>	TEM	TEM column stability	In line
	SEM-Electron diffraction and X-ray diffraction	Spatial resolution	In line
<b>Morphological analysis</b>	Top view CD-SEM	3D information	In line
	3D-AFM	3D structures	In line
	X-ray reflectometry and scattering	Spot foot print	In line
	Spectroscopic ellipsometry	Spectral range Spatial resolution	In line
	Ellipsometric porosimetry	Microporous	At line
<b>Mechanical analysis</b>	Acoustic waves	Spatial resolution	In line
	Four point bending	Environmental	Off line

of 300mm wafers requires alternative solutions like FIB sampling on full wafer for TEM.

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