Workshop in the frame of the 3DAM European ECSEL Project

March, 15th 2019 - Titane 1 room, Maison MINATEC, Grenoble

As nano-electronics, technology is moving beyond the boundaries of (strained) silicon in planar or finFETs, new 3D device architectures and new materials bring major metrology and characterization challenges which cannot be met by pushing the present techniques to their limits. 3DAM "*3D Advanced Metrology and materials for advanced devices*" is an EU-funded pathfinding and assessment project focusing on innovations and progress in metrology and characterization related to the latest generation of 3D front-end of line (FEOL) and back-end of line (BEOL) structures (fins, nanowires, TSVs) as well as 2D materials :

- ***Dimensional metrology***: *3D-SPM, CD-SEM, OCD*
- ***Structural analysis***: *Electron Tomography, PL & CL, SHG, GHz-SAM, X-ray NanoCT*
- **Compositional/dopant analysis**: *SIMS, APT, STEM-EDX and EELS, IRR, Raman, HRXRD*
- ***Carrier distribution and mobility***: *3D-SSRM, micro-multi-point probes, THz spectroscopy*
- ***Strain and stress***: *HRXRD, Raman, Precession Electron Diffraction in a TEM*

The goal of this workshop is to disseminate the results of the projects to the public. The combination with the insights and learnings from experts will make this one-day workshop an up-to-date overview of the most recent advances in the analytical techniques and diagnostic capabilities essential for technology development.

Keynote Speakers:
Dr. Maud Vinet (LETI)
Prof. Dr. Ehrenfried Zschech (Fraunhofer Institute)
Invited Speakers:
Dr. Delphine Le Cunff (ST Microelectronics)
Dr. Zineb Saghi (LETI)
Dr. Igor Turovets (NOVA)

Committee Co-Chairs:
Dr. Vincent Delaye (LETI)
Dr. Laurens Kwakman (Thermo Fisher Scientific)

Registration & Information via YURPLAN **, registration deadline March 8th**

Program and abstracts: next pages

Program

08:30	Welcome Coffee
09:00	***Opening*** **Frank de Jong,** 3DAM Coordinator (Thermo Fisher Scientific)
09:10	***Towards new computing paradigms: advanced CMOS & memory roadmap and consequences for metrology*** **Maud Vinet,** Advanced CMOS Manager (CEA, LETI)
09:55	***3D metrology and diagnostics at multiple length scales – Status and outlook*** **Ehrenfried Zschech,** Department Head of the Fraunhofer Institute for Ceramic Technologies and Systems IKTS (Fraunhofer Institute)
10:40	Coffee break
11:10	***Inline Metrology Challenges and Future Trends*** **Delphine Le Cunff,** Principal Metrology Expert (ST Microelectronics)
11:45	***Understanding Peculiar Luminescence Spectral Features In InGaAs Fins By Colocalized Cathodoluminescence And Electron Microscopy*** **Chiara Sinito** (Attolight) **and Nicolas Bernier** (CEA, LETI)
12:05	***Advanced optical testing of 3D devices*** **Zsolt Szekrényes** (Semilab)
12:25	Lunch
13:30	***3D Chemical Analysis of Complex Nano-devices by Analytical Electron and Atom Probe Tomography*** **Zineb Saghi,** Senior Research Engineer (CEA, LETI)
14:05	***Compositional and strain metrology in nanoscale structures using Raman spectroscopy*** **Tomas Nuytten** (imec)
14:25	***Recent advances in strain metrology for 3D devices and novel materials using X-ray based techniques*** **Juliette van der Meer** (BRUKER)
14:45	Coffee break
15:15	***3D (in-line) metrology challenges and solutions*** **Igor Turovets,** Senior Research Scientist (NOVA)
15:50	***Challenges in Failure Analysis and Physical Characterizations of 3D structures*** **Nadine Bicais-Lepinay** (ST Microelectronics)
16:10	***Statistical Significance of STEM and STEM-EDX based Metrology on Advanced 3D Transistor Structures*** **Laurens Kwakman** (ThermoFisher Scientific)
16:30	End of the Workshop

Abstracts

Towards new computing paradigms: advanced CMOS & memory roadmap and consequences for metrology

Maud Vinet (CEA, LETI)

In this presentation, we will share the advanced CMOS and memory technological roadmaps that supports the evolution of computing and storage. To cope with power consumption, the memory wall, the data deluge, new memories and logic devices architectures will be introduced. They rely on dedicated integration flows, introduction of new materials, alternative geometries. We will review what the expectations in terms of metrology capabilities are.

3D metrology and diagnostics at multiple length scales – Status and outlook

Ehrenfried Zschech (Fraunhofer IKTS Dresden, Germany)

Metrology and diagnostics, process control and physical failure analysis, are driven by the continuous shrinkage of feature sizes for both active devices and interconnects, new device architectures and advanced materials stacks. Innovations in metrology strategies and techniques are critical to enable the implementation of new devices and technologies and to control advanced manufacturing processes. Fast diagnostics and failure analysis are needed to ensure high yield and the required product quality. Metrology gaps exist particularly for non-destructive 3D structure characterization.

This talk will discuss the pressing needs and technical challenges for X-ray based 3D metrology and diagnostics capabilities to support advanced technologies at wafer level as well as for assembly and packaging. The intrinsic advantages of nondestructive X-ray computed tomography (XCT) in the fields of 3D imaging, physical failure analysis, and metrology of electrical interconnects in semiconductor products for both advanced packaging and on-chip interconnect structures will be demonstrated. Advanced packaging solutions, particularly 3D integration technologies, are boosters for performance and functionality of microelectronic products. However, at the same time, 3D heterogeneous system integration becomes increasingly challenging for product reliability. This talk will address the nondestructive localization and characterization of defects in interconnects to mitigate reliability-limiting effects in 3D IC stacks. Particularly, the geometry of 3D Through-Silicon-Via (TSV)/micro-bump stacks and defects (voids and micro-cracks) in these metallic structures as well as micro-crack evolution in Cu/low-k Back-End-of-Line (BEoL) stacks caused by thermomechanical stress (Chip-Package Interaction, CPI) will be discussed.

Perspectives to overcome two major limitations of state-of-the-art nano XCT tools, i.e. the necessity of sample preparation (typically less than 50 μm thickness, depending on the material composition, if 8 keV photons are used) and low imaging throughput, will be discussed. A novel tool concept for laboratory X-ray microscopy at high photon energies, using advanced X-ray sources with high flux and advanced X-ray optics with high efficiency at photon energies > 10 keV, will be presented.

Inline Metrology Challenges and Future Trends

Delphine Le Cunff (ST Microelectronics)

It is common sense to say that inline Metrology is a powerful enabler to ramp up pilot lines and to improve the yield in mature factories. It reduces the cost of manufacturing and the time to market for new products introduction bringing valuable and extensive characterization of processes and products. Over the years to fulfill technology requirements, while dimensions continuously shrank, layer thickness reached the atomic scale and new 3D architecture get introduced, inline Metrology constantly had to evolve and adapt. At the same time, ICs demand expand in the automotive market leading to a reinforcement of the quality requirements associated with measurement system and product control plan management. Though, the real challenge was to maintain the same level of performance for the key Metrology criteria namely accuracy, sensitivity, capability and productivity.

From the technical perspective, since the development of technology nodes below 45nm, classical inline Metrologies mostly based on optical techniques and scanning electron microscopes were in some cases reaching their limits. For thin and ultrathin films metrology, the industry had to rapidly adopt X-ray based techniques such as XPS, HRXRD, XRR which were traditionally restricted to offline laboratories. For Optical CD measurements, the complexity of the pattern structures leads to the introduction of Muller matrix and to the combination of multiple optical modules for model fitting, while overlay techniques moved from image based to diffraction based techniques. To push the limit, other alternatives such as Hybrid metrology combining the data from complementary techniques are explored [D. Le Cunff, Journal of Micro/Nanolithography, MEMS and MOEMS, Vol 13 (4), 041402, 2014]. Overall, Metrology techniques evolved to complex model-based techniques that requires a deep knowledge and understanding of nano-scale materials properties and of physics. This actually reinforced the link between Metrology, Physical Characterization and Physical modeling domains allowing innovative studies such as local stress measurement [A. Durand, Proceedings IEEE International Conference on Nanotechnology (27-30 July 2015, Roma, Italy)] and ultrathin SOI film optical modelling [L. Schneider, Proceedings IEEE/SEMI Advanced Semiconductor Manufacturing Conference (May 4-6, 2015, Saratoga Springs, NY, USA)]. As in close connection, inline Metrology continues to evaluate offline laboratories techniques (Photoluminescence, Raman Spectroscopy…) that could be adapted to industrial requirements for potential future adoption.

In the frame of industry 4.0 evolution, combined with High Volume Manufacturing requirements, Metrology techniques themselves and more specifically the way the information is extracted from the given signal or image can again evolve. Indeed, with the introduction of Neutral Network and Deep Learning algorithms, the raw signal can be exploited in an advanced statistical way to extract the maximum level of information out of a measurement step [J. Ducoté, Proceedings European Mask and lithography Conference (19-20 June 2018, Grenoble, France)]. The driver is no more to extract a precise physical quantity but to detect anomalies as early as possible in the fabrication process flow. This actually paves the way for new bridges with inline defectivity techniques.

Understanding Peculiar Luminescence Spectral Features In InGaAs Fins By Colocalized Cathodoluminescence And Electron Microscopy

Chiara Sinito (Attolight) **and Nicolas Bernier** (CEA, LETI)

CEA-LETI has been developing and testing over the last few years an advanced method to cross-correlate cathodoluminescence (CL) and transmission electron microscopy (TEM) on III-V materials, with the objective to investigate how the morphological and chemical properties impact the local luminescence spectral features [J. Roque et al. Journal of Vacuum Science & Technology B 36, 042901 (2018) & J. Roque et al., Appl. Phys. Lett. 112, 202104 (2018)]. In the framework of the EU project 3DAM, the CL-TEM cross-correlation method was applied to InGaAs fins produced at *imec* to understand the origin of peculiar luminescence spectral features. The CL analysis performed at Attolight revealed that the luminescence spectra observed on the top view of this sample can be fitted using two luminescence energies: 0.78 and 0.8 eV. A line of InGaAs fins showing strong CL spectral contrast between these two energies was then extracted by focused ion beam (FIB). This lamella was characterized by TEM in terms of high-resolution imaging, strain mappings by precession electron diffraction (PED), electron Energy Loss Spectroscopy (EELS) and elemental mappings by energy-dispersive X-ray spectroscopy (EDS). The cross section TEM analysis revealed strong variation of indium content and tensile stresses along the fin. We show that these spatially correlated results allow for an accurate interpretation of the luminescence features observed on this sample.

Advanced optical testing of 3D devices

Z. Szekrényes (Semilab)

The ability to provide non-contact and non-destructive metrology solutions for composition, doping and defect monitoring of complex semiconductor structures is a key requirement of the semiconductor industry. Semilab designs and produces metrology equipment for the characterization of semiconductor devices with high flexibility to integrate different optical metrology heads into automated in-line or at-line platforms. During the 3DAM project, Semilab has explored different optical metrology possibilities (Raman, photoluminescence and infrared reflectance) to obtain a status update of these techniques to assess compositional and doping properties of semiconductor structures such as SiGe and III/V-based fins.

Semilab has carried out experiments with Model-Based Infrared Reflectometry (MBIR) on SiGe fin structures. The main goal was to monitor SiGe composition and carrier concentration in blanket test pads. Theoretical considerations show that the technique can be extended to 3D nanoscale device structures [Duru et al, 2013. - MBIR for In-line Doping Metrology of Epitaxial SiGe:B and SiC:P Layers, ASMC 2013 SEMI Advanced Semiconductor Manufacturing Conference]. In order to do this, Semilab has developed an appropriate effective media approximation and verified the sensitivity to compositional variations. The method turned out to be sensitive to process changes, thus it would be suitable as a go/no go process method due to the high speed and reliability of optical measurements. While the fin dimensions may also be measured by some other optical techniques, the P-dose measurement capability is unique for MBIR.

3D Chemical Analysis of Complex Nano-devices by Analytical Electron and Atom Probe Tomography

Zineb Saghi (CEA, LETI)

The continuous shrinkage of semiconductor devices and the use of complex geometries requires the development of powerful 3D characterization techniques. Atom probe tomography (APT) [Gault et al. Atom Probe Microscopy. Springer Series in Materials Science (2012)] and analytical electron tomography (AET) [S. Collins and Paul Midgley, Ultramicroscopy 180, 133 (2017)] are excellent tools for 3D nano- and sub-nanoscale characterization of nanomaterials. In this talk, we will show the recent advances in both techniques, and employ them for the 3D morphological and chemical analysis of Fin Field-effect transistors (FinFET) and III-V semiconductors. We will also highlight the limitations of each technique and discuss the recent interest in combining both methods for a more comprehensive understanding of the nanostructures. Data fusion is a challenging task but is necessary to reliably interpret the data. For instance: AET provides 3D analysis of larger fields of views with higher spatial fidelity than APT, but has more limited spatial resolution and composition sensitivity. Within the framework of 3DAM project, we intended to correct the distortions and local atom mixing in the reconstructed APT volumes by using the electron tomography volumes as prior knowledge. We will show that APT (fully quantitative) reconstructions can also be used to validate the quantification methods currently developed by the AET community [P. Burdet, Z. Saghi et al., Ultramicroscopy 160, 118 (2016)].

Compositional and strain metrology in nanoscale structures using Raman spectroscopy

Tomas Nuytten (imec)

The introduction of novel channel materials SiGe and Ge in semiconductor technology is accompanied by an increased need for local stress and composition measurements in these materials. Electron microscopy-based techniques such as NBD and CBED provide unparalleled spatial resolution but involve destructive sample preparation, while high-resolution X-ray diffraction requires long measurement times when the region of interest is brought to limited dimensions. Recently however, it was found that a periodic array of semiconductor fins can act as a photonic crystal where the incident light is focused into the channel material and light transmission into the surrounding oxide is forbidden. This confinement of visible excitation light into the region of interest has re-enabled the application of Raman spectroscopy for the purpose of stress and composition measurements in structures far beyond the diffraction limit. High-NA Raman spectroscopy which is required for the unambiguous characterization for anisotropic stress profiles, can be combined with intrinsic enhancement effects to reach quantitative stress metrology without the need for additional sample preparation. Additional optimizations of the excitation mechanism such as the use of linearized polarized light or off-axis excitation can be implemented to further enhance the accuracy of the measurement, and to propose a truly industry-compatible stress and composition characterization technique.

Recent advances in strain metrology for 3D devices and novel materials using X-ray based techniques

Juliette van der Meer (BRUKER)

High-Resolution X-ray Diffraction (HRXRD) is a well-established technique for the characterization and metrology of epitaxial materials encountered in a variety of important technologies such as nano, opto and power electronics. Traditionally the technique was mainly used for blanket films, and this is still a significant application. However, complex epitaxial nanostructures continue to grow in importance to enable advanced CMOS logic transistors that must combine high-performance with low power consumption and cost with scaled dimensions. Hence, the need to measure and analyze such structures becomes necessary. Several new transistor architectures being considered for logic nodes beyond 10 nm, including more sophisticated FinFETs, gate-all-around (GAA) FETs and the use of fully-depleted silicon-on-insulator (FDSOI) substrates. Equally varied is the range of epitaxial materials proposed, which include SiGe, SiP, Ge as well as III-V materials. Each of these innovations has specific challenges for both process development and control. In this presentation we will discuss the recent advances in HRXRD tools, measurements and analysis methods for the characterization and metrology of arrays of nanostructures on patterned wafers with a spot-size < 50 µm and production worthy throughputs and reliability. We will discuss how HRXRD measurements such as high-speed reciprocal space maps (RSMs) are used to determine the composition, strain, and quality of epitaxial nanostructures, and illustrate the challenges and results using representative examples drawn from our recent collaborations.

3D (in-line) metrology challenges and solutions

Igor Turovets (NOVA)

In this presentation we will address the current and future 3D complexity in logic and memory semiconductor manufacturing and the metrology challenges they create. We will address the current trends for metrology usage and the needs for combinations of different off-line and in-line techniques (LAB2FAB and FAB2R&D), as well as combination of Stand Alone and integrated metrology (and tool sensors) to get best accuracy and required sampling with minimal Cost of Ownership. We will discuss metrology approaches for 3D materials and critical dimension measurements, with a focus on hybridization of Optical CD with different metrology tools, such as CDSEM/TEM/XPS/XRF/AFM and different aspects of Machine-Learning usage in High Volume Manufacturing.

Challenges in Failure Analysis and Physical Characterizations of 3D structures

N. Bicais-Lepinay (ST Microelectronics)

Today's laboratories supporting semiconductor manufacturing must deal with shrinking devices geometries, new integrated materials and novel architectures. The conventional 2-dimensional imaging with SEM or TEM becomes in some cases insufficient to characterize critical devices. During the presentation, we will present three real case studies combining various techniques to better characterize 3D complex structures.

Micro-lenses are resist made objects on top of a pixel architecture, used to concentrate photons into the photodiode. Their semi-spherical shape must be accurately controlled to ensure the best light focusing. 3D metrology is therefore required to validate the expected curvature of the etched resist. If AFM enables to monitor the topography of such a micro-scale object, the size of the AFM tip limits this technique capability to map the gap depth between two adjacent lenses. FIB SEM tomography [Lepinay, K., and F. Lorut. "Three-dimensional semiconductor device investigation using focused ion beam and scanning electron microscopy imaging (FIB/SEM Tomography)." *Microscopy and Microanalysis* 19.1 (2013): 85-92] here appears as a right complementary technique. Compared results on twin samples will show how FIB/SEM tomography can be used as a complementary metrology technique.

In the case of Phase Change Memory (PCM) technology, a chalcogenide poly-crystalline material based on ternary alloy GexSbyTex (GST) is integrated in memory architecture. Advanced localized characterization techniques are mandatory to study material properties of GST during the process flow or after a change of memory states (Set/Reset) in specific cells. TEM based techniques such as STEM imaging, Energy Dispersive X-ray Spectroscopy (EDS) or NanoBeam Diffraction (NBD) can provide deep information on crystalline/amorphous state, elements local distribution or microstructure [Valery, A., K. Dabertrand, R. Bon and L. Clément. “The use of advanced TEM-based characterizations for bits fail analysis in 28 nm Phase Change Memory products”, MAM 2019, pending]. Complementary to these techniques, electron tomography enables to render material inhomogeneity of a whole cell.

Dopant related failure analysis reveals itself as a tricky operation: not only dopant traces may be undetectable with conventional TEM techniques (STEM/EDX, EELS), but the choice of the cut direction can be somehow random without a prior knowledge of the dopant distribution. SCM (Scanning Capacitance Microscopy) is an AFM technique aiming at observing dopants. Coupled with a FIB based sample preparation [F. Lorut, A. Valéry, N. Chevalier and D. Mariolle. « FIB Based sample preparation for localized SCM and SSRM". ISTFA proceeding 2018: 209-213], it is thus possible to localize accurately dopant marginalities in a failing device. Moreover, it enables to combine both SCM imaging and STEM/EDX.

Statistical Significance of STEM and STEM-EDX based Metrology on Advanced 3D Transistor Structures

Laurens Kwakman (ThermoFisher Scientific)

Patterning processes need to be controlled on critical parameters such as CD, LWR/LER, pitch-walk and structural bending. While STEM based metrology has sub-nm precision, a single measurement is not representative for the device dimensions, known to vary statistically (LER/LWR) as well as systematically (Pitch-walk, structural bending).

Only when measuring many individual FinFET structures automatically, CD, LER and LWR can be quantified from the distribution of measured line widths and line pitches, SADP and SAQP induced pitch-walk may show up as multi-modal pitch distributions, and pitch walking can be quantified if also structural bending is properly taken into account.

In this study the relevance of STEM metrology statistics is demonstrated and illustrated via several examples.

Moreover, the STEM metrology capabilities are evaluated with different P/T ratio and Variability ratio (r) indicators and for different, HVM control and Technology development support use cases.

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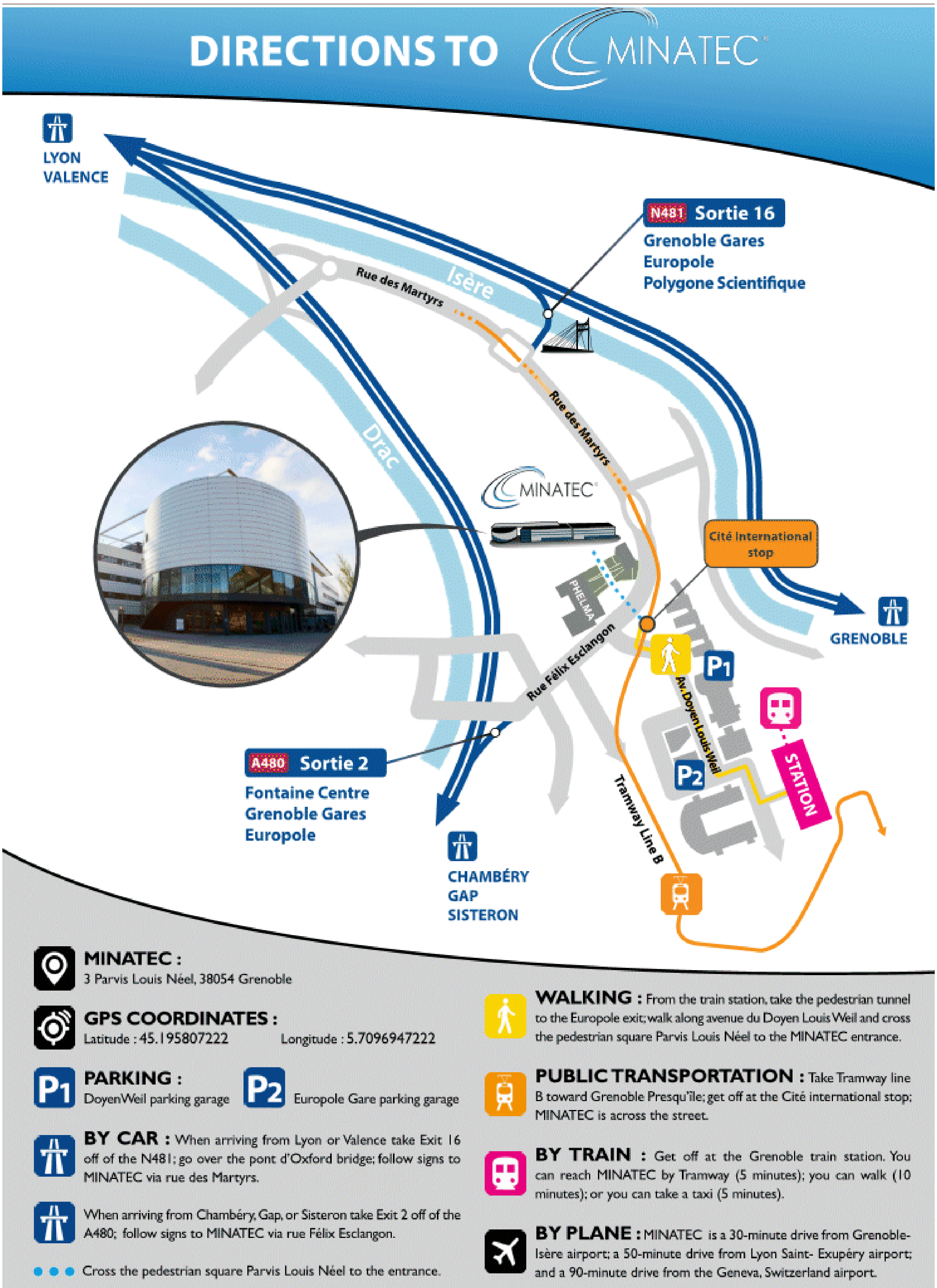

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