Nano-RF is a European project and the main concept is the development of CNT & graphene based advanced component technologies for the implementation of miniaturized electronic systems for 2020 and beyond wireless communications and radars.
The developed components and technologies developed during the project will be implemented in the following *demonstrators*:

- Reflect array antennae for wake vortex and weather radars
- Graphene receiver module

The demonstrators will exhibit the reconfigurability, systemability, integratability and manufacturability of the developed technologies and unify advanced More-than-Moore elements and Beyond-CMOS devices with existing technologies. It addresses "System Perspective" to support miniaturized electronic systems for 2020 and beyond.
This Nano-RF newsletter intends to present the latest progress obtained during second year of the project.

Design and Simulation activities

➢ Simulation of CNT/graphene devices

On the year of the project, a self-consistent Poisson-Schrödinger solver with a user friendly interface has been developed. The multiband carrier transport (Schrödinger equation) and the electrostatic potential (Poisson equation) throughout the device are simultaneously solved by numerical iteration. The solver is compatible for CNTs or graphene devices. Figure 1 show the solver in the case of CNTs.

The solver allows the control of geometry (channel size, gate radius), as well as quantistic parameters (number of electronic bands, transfer energies among carbon atoms, etc.), electrical parameters (applied voltages, electrical permittivity of the medium around CNT, etc.), and numerical parameters. The grahene solver and an example of the user friendly interface are presented in Figure 2

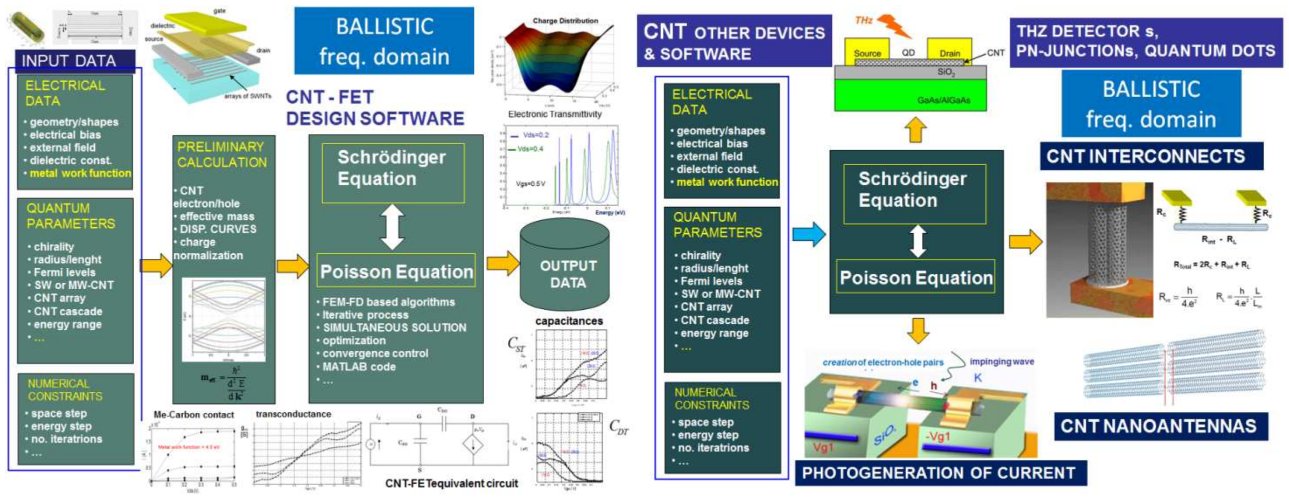

Figure 1 : The UNIVPM solver for the simulation of CNT devices/circuits, in the ballistic regime, frequency (energy) domain

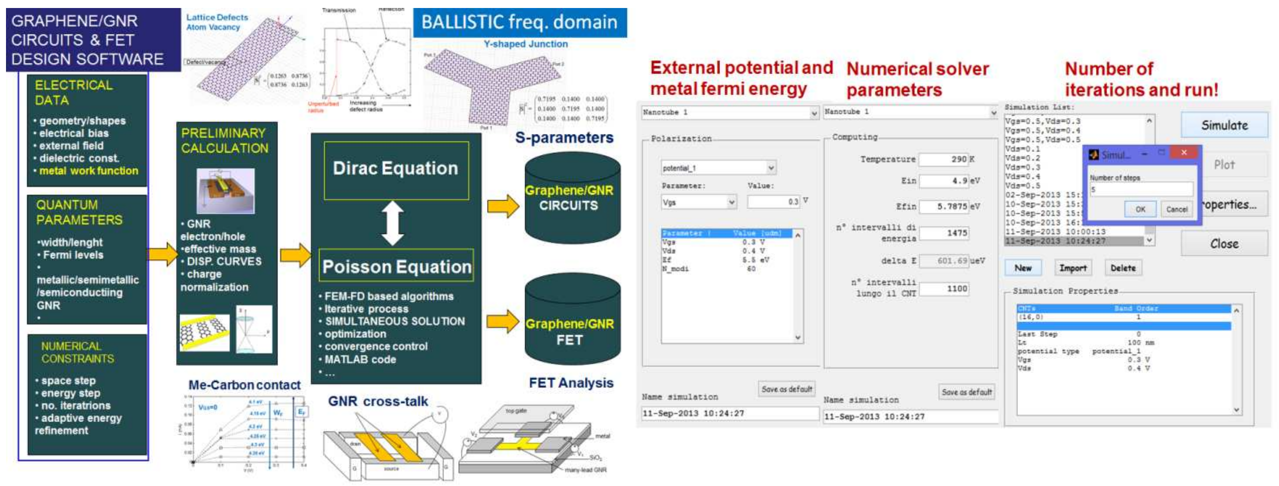

Figure 2 Left: the UNIVPM solver for simulation of graphene/GNR devices/circuits, in the ballistic regime, frequency (energy) domain. Right: example of the user-friendly interface. The code is written in Matlab

Fabrication activities

➢ CNTs devices fabrication and characterization

- **CNTs switch**

- **3D interconnect with CNTs**

The yield of the densification and transfer process by introducing BCB based transfer technique has been improved. We have also developed the stacking process to enable multi-layer 3D interconnect structure using CNT bundles. Figure 3 show the double layer CNT interconnect stacking and the resistance measurement results of both one layer double layer CNT vertical interconnects.

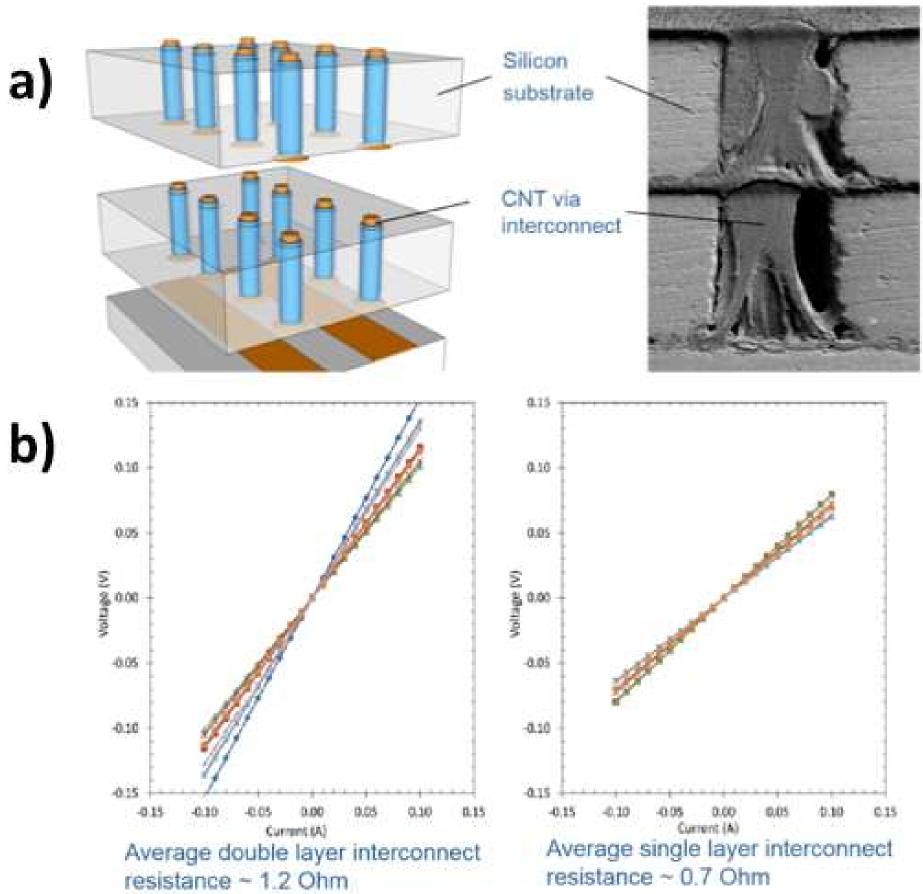

Figure 3 : a) SEM picture of CNT vertically aligned obtained by TCVD for 3D interconnect application b) Resistance measurement results of CNTs vertical inteconnects

- **<u>CNTs FET</u>**

For the CNT FET application, the CNTs growth optimization is necessary. We need to grow horizontally aligned single-walled CNTs (SWCNTs) for device fabrication. In this case, the substrate and growth conditions as well as the required gas concentration are very different in comparison with classical growth. For example, we used ST-cut quartz substrate rather than Si substrate so that the growth of SWCNTs can follow the crystal direction of the substrate surface. On the other hand, we installed new gas sources in our growth system, because for horizontally aligned SWCNT growth, it is very low concentration of carbon atom required and methane is the best choice. Figure 4 present the result of the growth after optimization. As we can see, there is a big improvement in term of CNTs density.

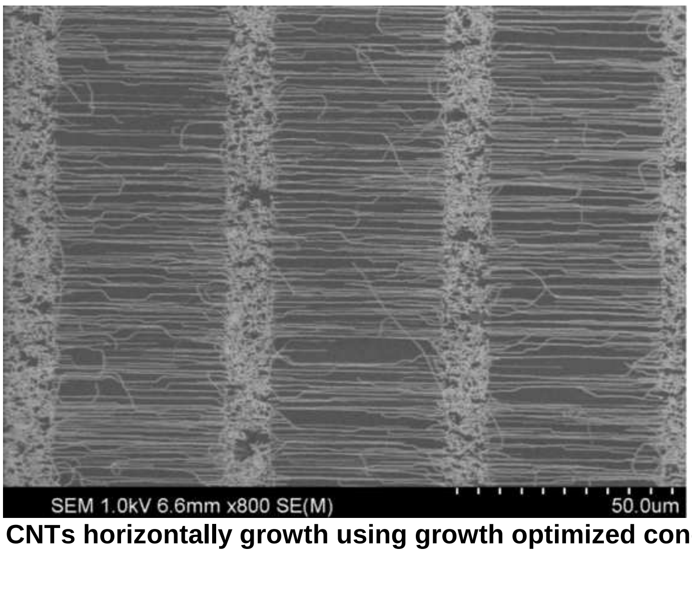

Figure 4 : CNTs horizontally growth using growth optimized condition

- **CNTs antenna**

Optimized designs on highly resistive Silicon and quartz substrates have been selected and transferred to TRT for process (Figure 5). This final layout allowed the fabrication of sixteen individual CPW CNT-based monopoles, allowing the experimental influence of some keys parameters over measurement results, such as CNT bundle diameter and length, RF access geometry and surrounded ground plane design.

Deembedding structures have been also inserted for S-parameter on-wafer calibration standards determination and also for Material parameters extraction (ε, μ).

Figure 5 : Generic layout for CNT-based monopole in CPW technology (HR Si and quartz substrate)

Following the design, first CNTs antenna has been fabricated. On Figure 6a, we can see the structure realized before CNTs growth. Technological processes matching with expected antenna design have to be overcome, as CNT diameter-to-length ratio is critical (Figure 6b). Some process procedure and design modifications are under work to overcome fabrication constraints.

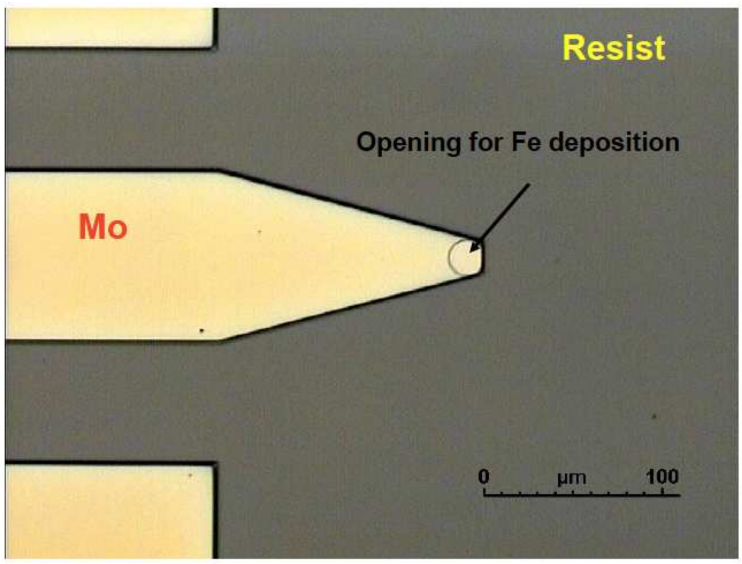	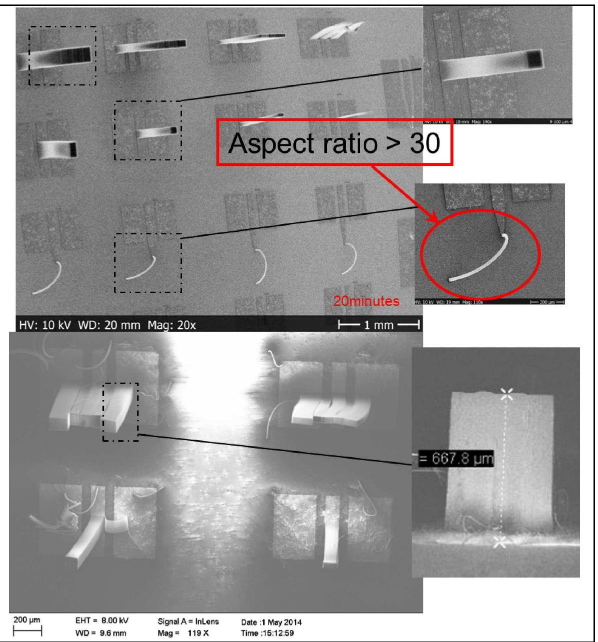
(a)	(b)

Figure 6 : (a) CNTs antenna fabrication and (b) After CNTs growth

➢ Graphene Growth

A major objective for the project is to obtain graphene on a large scale with a good quality for devices fabrication. So, we had worked towards developing a growth process for large area monolayer graphene on SiC. The carrier mobility is of main concern which implies good understanding and control of defects and other non-uniformities that can act as scattering centres.

Growth of epitaxial graphene on Si face of SiC substrates was carried out in an inductively heated furnace at a temperature of 1950℃ and at an ambien t argon pressure of 1atm. Graphene surface morphology, thickness, structure and composition have been assessed by using AFM, EFM ,LEEM, Raman spectroscopy and mapping, and XPS.
To improve the growth process, new growth equipment was designed and built having some beneficial characteristics. The new system has a longer RF-coil with uniform distance between the pipes and also the possibility to move coil up and down to change the temperature gradient for both etching the SiC substrates and epitaxial graphene growth. Here it is possible to perform thermal etching of the SiC substrate prior to graphene growth.

We have studied the effect of argon pressure on graphene layer thickness and the thickness uniformity (graphene layer continuity). We have shown that the higher argon pressure result in thinner and more uniform graphene layer, while with low pressure the thickness can be increase but not uniformly. The effect of temperature distribution was also studied. For this study we have used a symmetric crucible to have better temperature uniformity and also study the effect of temperature difference in the cell (crucible) on the thickness uniformity. These results contributed to the optimization of the growth process.

Epitaxial graphene on SiC is a very stable material as to treatment by different liquid agents. However we observed that the open atmosphere starts influencing the epitaxial graphene in terms of adsorption after one or a few months of its growth. The rate of adsorption is found to be different on different areas of same sample which confirms that the surface morphology of the sample plays a significant role in this mechanism. Here we tried to identify the adsorbates, the reason behind surface modification of graphene and how to avoid adsorption. Large area samples e.g. 20x20 mm2 have been grown and characterized as to their thickness homogeneity.
Large area AFM image in phase contrast mode illustrates that a second layer is preferentially formed on the step edges and it appears as long nano-ribbons.

In order to enable express characterization of graphene with a fast feed back to the growth process parameters we have developed a combined optical method comprising Raman mapping and reflectance mapping which is made at the same laser wave length . This technique can give thickness mapping which is the most useful but also mapping of different graphene characteristics extracted from the Raman spectra.

➢ Graphene devices fabrication and characterization

- **<u>Graphene characterization</u>**

We had successfully developed and implemented a novel experimental technique to measure the thermal conductivity in membranes and thin films. The method is based on the concept of Raman thermometry, however with the decisive difference that heating of the sample and probing of the temperature are decoupled by using two spatially independant lasers with different wavelength (Figure 7, left). While a high power, near UV « heating laser » is used to produce a thermal hotspot, a low intensity "thermometer laser" measures the spatial distribution of the local temperature through the temperature dependent shift of a specific Raman mode of the investigated sample. The approach provides sub-micrometer spatial resolution while maintaining the direct imaging capability of the temperature distribution

The temperature distribution as obtained by a 2-dimensional map scan of a 1 µm thick Si membrane is displayed as proof of concept (Figure 7 midle). The right panel of show a line scan through the centre of the membranes for two membranes with thickeness of 1 µm and 9 nm. The obtained thermal maps contain information both about the thermal conductivity and the heat transport regime. The thermal conductivity can be determined by fitting the temperature decay using an appropriate heat diffusion model, whereas the heat transport regime is given by the shape of the thermal decay.

As the fabrication of modules and devices in the project NANO-RF progresses, we intend to apply this technique also to graphene FET in order to identify thermal hotspots and measure the heat distribution in these kind of structures and devices.

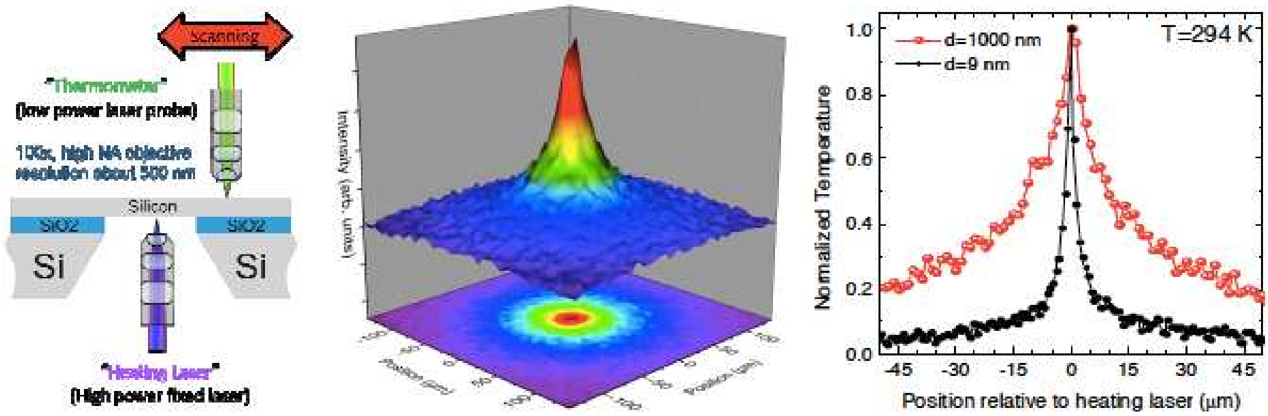

Figure 7 : Schematic illustration of the 2-laser Raman thermothry experimental setup (left), 2D thermal map of a 1 µm thick free standing Si membrane (middle), and thermal line scan for two membranes with different thicknesses of 1 µm and 9 nm (right).

- <u>**Graphene FET**</u>
    - <u>**Graphene FET fabrication (Graphene FET Source-Drain miniaturization)**</u>

Optimization of the source drain distance with respect to the gate length is important to reduce access resistance and provide an optimum FET device.

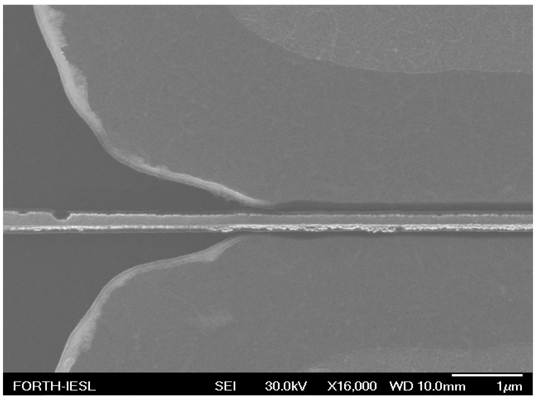

Figure 8: 0.2µm wide gate deposited in a 0.6µm wide Source – Drain distance. Source drain is deposited by optical lithography whereas the gate is formed using electron beam lithography.

The optimized process, combined with state of the art ohmic contacts, translates to reduced series resistance (6 Ohms) which is essential to the performance of a GFET.

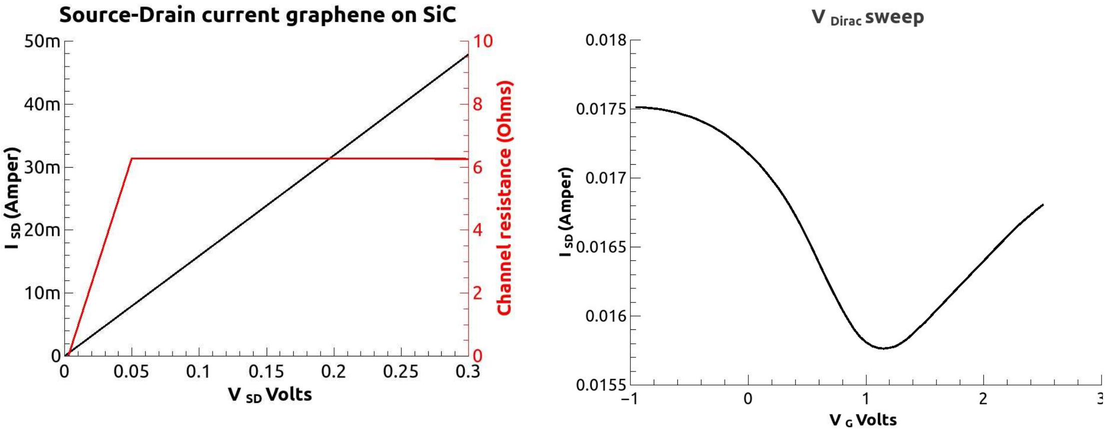

Figure 9: Low access resistance (<6Ohms) and the Dirac point accessible by gate voltage from devices fabricated on Graphene consortium material (SiC).

- ## <u>High k dielectric optimisation and depostion</u>

In accordance with the work objectives Tyndall has worked towards developing a room temperature e-beam process for the growth of high-κ metal oxides (ZrO2 and HfO2) suitable as gate oxides for graphene and CNT FET devices. In addition it is explore the route of a high–κ dielectric stack formed by a growth sequence of room temperature e-beam process followed by an Atomic Layer Deposition growth process.
During year 2 Tyndall developed new high-κ metal oxides growth by e-beam evaporation that has resulted in improvement of the quality of HfO2 thin films. As is shown in Figure 1.a, for a HfO2 thin film the thickness uniformity across a 4 inch Si substrate is better than 1 % while the refractive index is around 2.01 (n630nm) is this is indicative of for significant improvement in the HfO2 thin film stoichiometry.

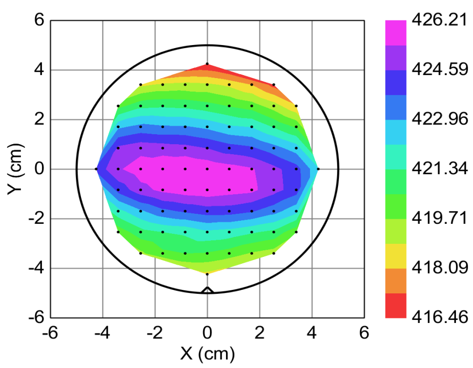

Figure 1.a) RT E-beam HfO_2 film thickness uniformity (in Å) across a 4 inch wafer

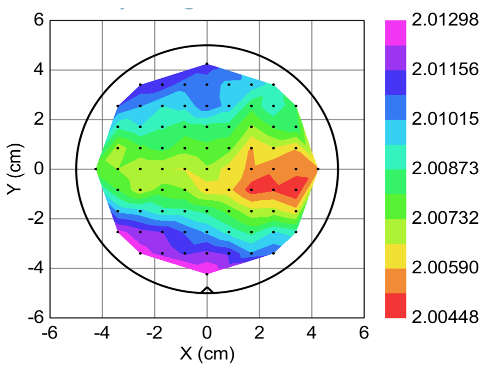

Figure 1.b) Refractive index (n, at 630nm) of the RT E-beam HfO_2 film across the 4 inch wafer

The Auger depth profile for the 40-nm thick HfO_2 thin film is shown in Figure 2 and confirms that the new E-beam process offer an improved control of the film stoichiometry.

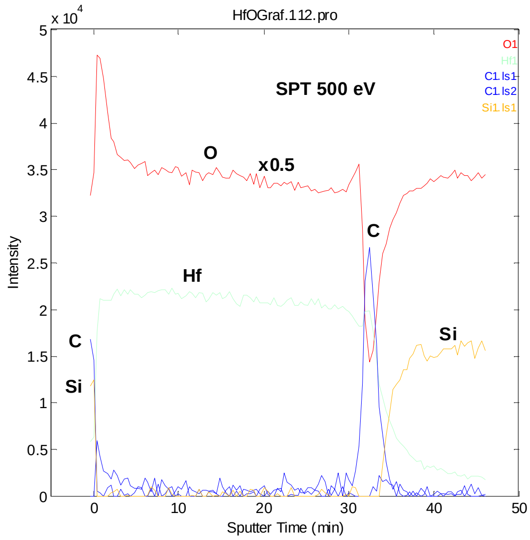

Figure 2. Auger Depth profile for the RT E-beam HfO_2 thin film (Thales)

In accordance with the work objectives, Tyndall has scaled down the RT E-beam process for the HfO_2 high–κ dielectric thin film from 15nm down to 5nm has been developed.

The XPS results presented in Figure 4 outlines that a good control of film stoichiometry is achieved by E-beam even when scaling down the HfO_2 film thickness to 5nm.

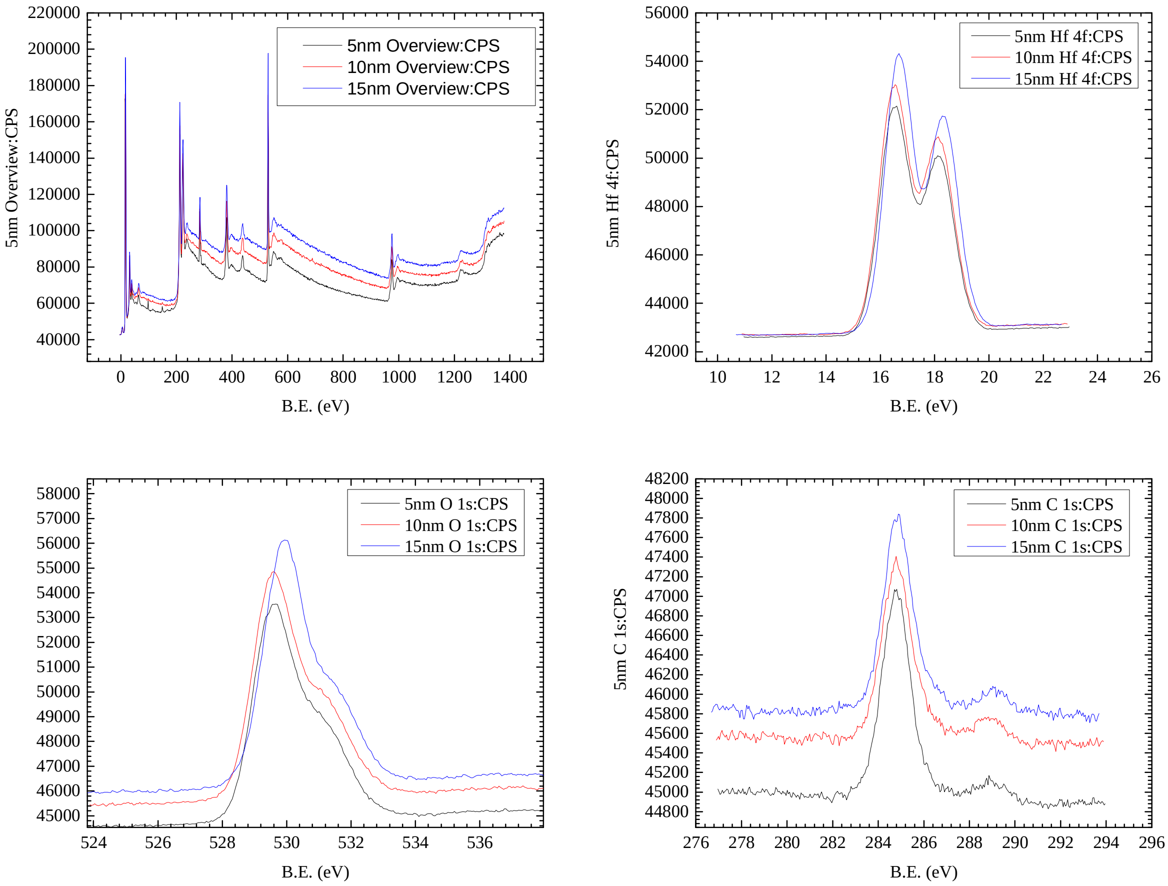

Figure 3. XPS results on HfO_2 thin films (5,10 and 15nm; *NANO RF-13, NANO RF-14 and NANO RF-15, see Table1*) grown on Si at RT by E-beam (ICN): Survey spectra, Hf4f, O1s and C1s spectra.

Table 2. Summary of main XPS results for the HfO_2 thin films (5, 10 and 15nm) grown on Si at RT by E-beam

Sample ID	Thickness (nm)	O/Hf ratio	Binding E of Hf $4f_{7/2}$
NANO RF-13	5	1.76	16.51 eV
NANO RF-14	10	1.74	16.50 eV
NANO RF-15	15	1.70	16.68 eV

Following the qualification of the E-Beam process for the HfO_2 thin films Tyndall current work on developing a process for the growth on CVD graphene.

Nano-RF Publications

In the last 12 months the partners of the Nano-RF project published various results related to the project.

- **Publications**

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- J. S. Reparaz, E. Chavez-Angel, M. R. Wagner, B. Graczykowski, J. Gomis-Bresco, F. Alzina, and C. M. Sotomayor Torres, "A novel contactless technique for thermal field mapping and thermal conductivity determination: Two-Laser Raman Thermometry", Rev. Sci. Instr. 85, 034901 (2014)
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➢ Conference

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- 6M.Aldrigo, M.Dragoman, A. Constanzo, and D. Masotti, Exploitation of Graphene as HIS and RIS for Devices in the MW and THz Frequency Ranges, European Microwave Conference, October 2014, Rome Italy.

- A novel high resolution contactless technique for thermal field mapping and thermal conductivity determination: Two-Laser Raman Thermometry" (oral) E. Chávez-Ángel, F. Alzina, and C. M. Sotomayor Torres, E-MRS spring 2014, 26-30 May 2014, Lille (France)

- "Heat propagation and thermal phonon dynamics in group IV nanostructures" (poster) M. R. Wagner, J. S. Reparaz, J. Gomis-Bresco, E. Chávez-Ángel, B. Graczykowski, F. Alzina, and C. M. Sotomayor Torres, E-MRS spring 2014, 26-30 May 2014, Lille (France)

- "Thermal conductivity and thermal field distribution determination in free-standing Si and Ge membranes" (oral) J. S. Reparaz, E. Chavez-Angel, M. R. Wagner, A. Shchepetov, M. Prunnila, J. Ahopelto, P. Vaccaro, I. Alonso, M. Garriga, A. R. Goñi, F. Alzina, and C. M. Sotomayor Torres, E-MRS spring 2014, 26-30 May 2014, Lille (France)

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- "Acoustic phonon dynamics in free standing group IV semiconductor membranes studied by ultra-fast pump & probe spectroscopy" (poster) M. R. Wagner, J. S. Reparaz, J. Gomis-Bresco, E. Chávez-Ángel, B. Graczykowski, F. Alzina, and C. M. Sotomayor-Torres, NanoSpain 2014, 11-14 March 2014, Madrid (Spain)

- "Impact of boundary scattering on nanoscale thermal transport properties in ultra-thin Si-based nanostructures" (oral) M. R. Wagner, E. Chávez Ángel, J. Gomis Bresco, J. Sebastian Reparaz, A. Shchepetov, M. Prunnila, J. Ahopelto, F. Alzina Sureda, and C. M. Sotomayor Torres, ASME 2013 International Mechanical Engineering, 15-21 Nov. 2013, San Diego (USA)

- "Raman thermometry as contactless method for thermal conductivity determination: The case of thermal conductivity reduction in Si and Ge" (oral) J. S. Reparaz, E. Chávez Ángel, J. Gomis Bresco, M. R. Wagner, J. Cuffe, V. Shah, M. Myronov, D. Leadley, A. Shchepetov, M. Prunnila, J. Ahopelto, F. Alzina Sureda, C. M. Sotomayor Torres, ASME 2013 International Mechanical Engineering, 15-21 Nov. 2013, San Diego (USA)

- "Thermal Conductivity of nm-scale Membranes by Raman Thermometry" (oral) E. Chávez-Ángel, J. S. Reparaz, J. Gomis-Bresco, M. R. Wagner, J. Cuffe, A. Shchepetov, M. Prunnila, J. Ahopelto, F. Alzina, and C. M. Sotomayor Torres, 26th International Microprocesses and Nanotechnology Conference, 5-8 November 2013, Saporo (Japan)

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- D. Mencarelli, L. Pierantoni, "Modeling and Simulation of Carbon Nanotransistors", *Invited Paper*, Proceedings of the *15th Intern. Conference on Nanoscience & Nanotechnology 2014 (N&N 2014),* INFN-LNF, Frascati, Italy, Oct. 6-7, 2014.

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