Contract –NMP4-CT-2006-016475

CARBonCHIP

Carbon Nanotubes Technology on Si IC's

SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

Nanotechnologies and nanosciences, knowledge-based multifunctional materials & new production processes and devices

Publishable Final Activity Report

Period covered: from 01-04-06 to 31-03-09

Date of preparation: 13-05-09

Start date of project: 01-04-06

Duration: 3 yr.

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Publishable final activity report

1. Project summary

The microelectronics industry has adopted carbon nanotube (CNT)-based devices as an important and high potential route for post-complementary metal oxide semiconductor (CMOS) nanoelectronics. CARBonCHIP is a Specific Targeted Research Project (STREP) project funded by the European Commission (EC) that addresses the potential of integrated CNT technology. Through an interdisciplinary approach, comprising collaborating researchers from university, research centres and industrial partners, CARBonCHIP is investigating catalysis, growth and integration of CNTs on-chip while considering up-scalability and compatibility and taking advantage of existing electrical functions and/or patterns on Si. This work is complemented by the development of methodologies for CNT analysis on-chip.

2. Overall project objectives and impact

- CARBonCHIP addresses the potential of the integrated CNT technology through an interdisciplinary approach based on research and development in (i) CNT catalysis, (ii) CNT growth, (iii) on-chip CNT technology, (iv) related analysis methodology for control of CNT properties and (v) CNT devices for nanoelectronics. In this respect, specific challenges includeAchieving catalyst control (in terms of activity and selectivity),Optimising single-wall carbon nanotube (SWCNT) synthesis (in terms of density, properties and location),
    - Providing a methodology for analysis of CNTs integrated into Si structures,Taking advantage of existing electrical functions and/or patterns on Si.There are three industrial participants in CARBonCHIP to address the

  challenge and feasibility of applying CNTs in Front-End-of-Line (FEOL) and Back-End-of-Line (BEOL) Si technology at an industrial scale.

- It was the vision of the project to integrate the knowledge of materials science and nanomanufacturing as a key enabler for future CNT-based nanoelectronics. To this end, CARBonCHIP contributes to a roadmap of CNT-based devices in FEOL and BEOL, extending Moore's law towards the year 2020 and beyond.
- CARbonCHIP addresses the materials properties, the related fabrication process and analysis methodology. These aspects are explicit objectives of the workpackages (WPs).

- The real innovation in nanotechnology based on CNTs in the long term is the interdisciplinary research approach to enable integration of CNT technology with Si technology.

3. Consortium composition

The consortium consists of an industrial end user, two renowned research centers, two small-to-medium enterprises (SME's) and a university (detailed in Table 1). The strength of this consortium is that it combines basic research from the university and innovative product development of SME's to the end user, through the state-of-the-art research and development infrastructure of research institutes.

Table 1 Participants details in CARBonCHIP.

Participant	Short name	Web site	Type	Country
Interuniversity **M**icro**E**lectronics **C**enter	IMEC	www.imec.be	RES	Belgium
Commissariat à l'**É**nergie **A**tomique- **L**aboratoire d'**I**nnovations pour les **T**echnologies des **E**nergies nouvelles et les **N**anomatériaux	CEA-LITEN	www-drt.cea.fr/scripts/home/publigen/content/templates/show.asp?P=178&L=FR&ITEMID=9	RES	France
Alchimer	Alchimer	www.alchimer.com	SME	France
Nanocyl	Nanocyl	www.nanocyl.be	SME	Belgium
Centre for Surface Chemistry and Catalysis, Katholieke Universiteit Leuven	COK-K.U.Leuven	www.biw.kuleuven.be/ifc/cok/home.htm	HE	Belgium
Intel Ireland	Intel	http://www.intel.com/community/ireland/	IND	Ireland

4. Project coordination

The project coordination is done by IMEC represented by Guido Groeseneken[1] as Project Coordinator (PC). From 01-04-06 until 30/05/08 the coordination was done by Caroline Whelan, also from IMEC.

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5. Project execution

WP1 - Catalysis and CVD deposition for SWCNTs

WP1 deals with the growth of CNTs on unpatterned substrates using standard, structured, and grafted catalysts combine in an effort to construct a chemical vapour deposition (CVD) phase diagram for CNT growth.

Starting from multi-walled CNT (MWCNT) growth processes available at IMEC and LITEN at the beginning of the project, the main achievements of this workspackage are described below.

During the first year of the project PVD thin film catalyst technology deposited by IBS have been developed and mastered up to a thickness of 0.5nm. It have been demonstrated that this technology can be used at a wafer level integration thanks to its reproducibility and homogeneity (deliverable 6) This technology have been used to develop different CNT growth processes:

A rather low temperature (640°C) SWCNT process on silicon substrate which gives SW with a diameter in the range of 0.8 to 1.3nm

A small diameter MWCNT process which allows growing dense forests (density between 5 10^{11} and 10^{12} cm^{-2}) of 4nm diameter tubes at a temperature of 580°C

These two different materials have been integrated in WP2 either in HGTS (SW) or VGTS (s_MWCNT) as initially planed. It have been decided that PECVD will not be investigated further due to its inability to produce SW and we have stick on CVD process as the most promising technique for integration of CNT for nanoelectronic.

A good understanding of the CVD processes has emerged from the phase diagram approach (deliverables 3 and 7) which gives a broad pictures of the CNT materials and of the process conditions (catalyst diameter and temperature) to master the CNT.

Among the results two are very significant:

The existence of nucleation lines which govern the minimum size of the CNT with a given structure that it is possible to grow

The basic understanding of the relation between the growth mechanism (Tip or base) and the tube diameter (deliverable 7, 12)

These results have a strong impact on the way to achieve dense materials for interconnects applications. Very interestingly this understanding is associated with operational process which allow to switch from one growth mechanism to the other and thus to chose the material properties.

The role of the catalyst oxidation state at the growth temperature is the key point which governs the growth mode and thus the kind of material that it is possible to obtain on various substrates. This point explains particularly well the CNT material obtained on oxides or metallic substrates and the different behaviors of Ni or Co as compared with Fe catalyst much more difficult to deoxidize.

IMEC has made significant contributions in developing different catalyst and underlayer combinations which can be directly applied to WP2 for CNT integration in Si technology, more specifically via (interconnection) applications. A number of constraints were imposed in terms of material selection when working in a p-line (semiconductor Fab) environment. The following were developed at IMEC in WP1:

1) High density (~$5x10^{11}$) vertically aligned uniform diameter (7-8nm) MWCNT synthesis using Fe (IBS –Liten deposited) on Titanium under-layers.

2) High density vertically aligned MWCNT (8-13nm) MWCNT on BEOL compatible under-layers (TiN, TaN) using thin film deposited Ni,Co,Fe ($\sim 1x10^{11}$)
3) High density vertically aligned (8-15nm) MWCNT from electrochemical deposited (ECD) Ni nanoparticles on TiN ($\sim 1x10^{11}$)
4) 200mm wafer growth of high density vertically aligned MWCNT (8-15nm) MWCNT on TiN using thin film deposited Ni

IMEC has developed and implemented a novel metal nanoparticle catalyst deposition technique using electrochemistry which can be directly exploited for CNT growth. When deposited on barrier under layers (TiN and TaN) it produces comparable catalyst densities to PVD deposition (Ni) at room temperature. We have identified the use of a plasma pretreatment step to efficiently activate the catalyst before CNT growth to maximise MWCNT densities. A metal carbide synthesis path during CNT growth has also been proposed.

The results on CNT occluded in zeolite achieved by KU Leuven have been very significant and the progress during the project very impressive.

During the first year successful synthesis of CNT inside of AlPO5 zeolite have been done with the synthesis of other zeolite with different pore size and a yield of pore filling of 12% with an innovative process of pyrolysis of phthanocyanine on VPI-5

The second year the selective synthesis of metallic SWCNTs occluded in zeolite have been done leading to a highly conductive composite proven by electrical testing performed at Intel Ireland. Temperatures below 500°C are envisioned for nanotube synthesis, leading to a process compatible with current CMOS technology platform.

The third year considerable progress has been made in the characterization of the occluded carbon species in the VPI-5 pore. New techniques have added considerably in the understanding of the nanotube formation in the large-pore zeolite, achieving 100% chirality and diameter control of double walled nanotubes (DWNT), with pore filling degrees considerably higher as for the AFI type zeolite. This results in a highly conductive composite with resistivities two orders of magnitude better as for the state of the art 4Å filled SAPO-5 crystallites.

These results coupled with the WP2 results showing the possible integration of these materials in via holes open a credible new route for future advanced interconnects.

The grafting of nano particles as catalyst has been successfully developed by Alchimer during the three years of the project using an original approach to achieve selective deposition inside via holes. Three successive routes have been investigated

The electrografting of an organometallic followed by it pyrolisis

The ion impregnation of an electrografted precursor

The nanoparticles selective deposition on an electrografted polymer

From the three routes the last one is the most innovative and promising. Indeed the nanoparticles which are oxides (iron, cobalt iron…) are synthesized and well controlled in diameter independently of the deposition process. The HEMA polymer is first electrografted on the bottom of via holes and then the nanoparticles are selectively deposited on the polymer thanks to the fine tuning of the interactions between the particles and the polymer. Selective deposition of 3nm particles in 100nm holes have been demonstrated with a density close to $10^{12}cm^{-2}$ a growth process which consist first in the polymer burning have been successfully developed. This method is promising thanks to the decoupling between particle diameter and density and to the selective deposition of catalysts which allow growing dense s_MWCNT forest

During the project a strong expertise have been gained in the characterization of the nano objects (tubes, particles...) among them it can be noted:
_The pick-and-place approach which has been developed by IMEC to extract CNTs from devices for further analysis. This tool have been developed, optimized and applied to characterize CNT growth processes. MWCNT and DWCNTs have been evaluated with this method.
_The AFM catalyst particle characterisation has been developed during the whole project up to the stage of achieving consistent results between IMEC and Intel
_New MFM microscopy has been investigated for catalyst characterisation
_Strong expertise have been gained with raman spectroscopy during the project thanks to a new tools well adapted to CNT characterisation and better and better samples available from the partners

WP2 - Growth of SWCNTs on patterned Si substrates
The results from WP1 together with those of WP3, the grafting of SWCNTs on unpatterned substrates, converge in WP2 where the different CVD growth processes and selected catalysts are used to guide a process flow for the integration of horizontal and vertical CNTs on patterned Si. Similar to WP1, in WP2, analysis methods are key to developing a successful approach to SWCNT growth on patterns leading to device characterization in WP4.

Horizontal connections between tips with SWCNT in HGTS have been demonstrated during the project however catalyst integration proved challenging. The measured resistances are within the decade of the best published value on metal, which is good considering that these values are obtained on silicon.

ECD of Ni nanoparticles (density and size controllable) and subsequent MWCNT selective to a sidewall was demonstrated. Directly bridging the electrode gaps provided significantly challenging. However, we demonstrated that a direct contact could be achieved and observed;

An effective ohmic contact could be formed. A dissipated power in each CNT was calculated in the order of 0.6mW. A current carrying capacity of 10^7-10^8 A/cm^2 was calculated. A negative Temperature Coefficient Resistance in the order of -0.003~ -0.007 % °C^{-1} was calculated.

Within the project our objectives in WP2 concerning the via integration have been met and we have successfully integrated dense materials composed of 4nm diameter tubes growing with a base growth mode inside via holes up to 140nm in diameter.

The estimated density of tubes in the bundles grown on via built on silicon is close to 4 10^{12}cm^{-2} and the density of conduction channels around 10^{13} cm^{-2} This is within one order of magnitude to the target. This result is very good and at least for the morphology close to the worldwide state of the art.

Integrations have been performed on two different materials with metal 1 being either silicon or TiN. The developed process of integration and growth the filling yield of via hole is very good, almost 100%.

This integration on silicon may be relevant for the first level of interconnects on source and drain of transistors. While integration on TiN can be relevant for CNT vias on copper line or other metal line.

We demonstrated a full 200mm integration flow for CNTs as interconnects which can be applied to metal 1 level and the metal contact level. We developed a method for low temperature (400ºC) CNT growth in BestO2 – PVD acing a 100% via filling and tube bundles directly comparable to the diameter of the via. CNT via density was shown to have one to one correlation with the density of the initial catalyst for Ni deposited nanoparticles (ECD) on TiN.

We identified the challenges in integrating CNTs as interconnects, namely;

- Control of catalyst deposition on pattered structure – ECD offers this when combined with a suitable substrate (semi(conducting)) underlayer isolated from top surface)

- PVD is acceptably when there is a difference between annealing/growth conditions at the via bottom relative to the top surface layer (usually oxide field)

- Growth of CNTs from the via sidewall had a negative influence on the measured via resistance. Hence, an optimised catalyst deposition technique is required (Liten- IBS and IMEC Ni PVD, and ECD)

- Chemical mechanical polishing (CMP) is dependent on CNT length and type of underlying oxide. Effective CMP was demonstrated on 200mm CNT incorporated vias through ECD capping of the polished CNT arrays

- Electrical measurements will always be dominated by the inherent resistance of the underlayer for non – uniform defective CNTs and low density via filled arrays.

- A new process flow was developed to produce structures capable of measuring CNT vias. Considerable effort was done to ensure an effective TiN bottom contact in the vias. A method of determining the quality of the bottom contact using electrochemistry was also outlined. This learning cycle will be applied in future integration.

Growth of carbon nanofilaments was achieved at 550 °C on the Best 02 patterned wafer whatever the Co precursor was used. It was shown than metal salt deposition can be a good method to achieve selective catalyst deposition into the vias of Best02 wafer and the localization of the catalyst can be improved using simple variations in the composition of the solvent or in a post treatment after drop deposition.

Zeolites were shown to have the ability to achieve the desired CNT density and perfect alignment, and even – in some instances – chirality control, in accordance with ITRS standards for future interconnects. As well as having a low growth temperature.

A new innovative patented method for oriented growth on BEST02 has been shown, and confined crystallization of zeolite material was proven. In this approach 100% filling of the hole with crystalline AFI was demonstrated along with VPI-5 and LTL type zeolites. This is a major advancement in the use of zeolite crystals for integrated nanotube synthesis.

Preparation by dissolution and sonication yields by far the best HREM image quality and is therefore the superior method for analysis of the structure of CNT's (diameter, number of shells, bamboo tube or fiber, particles inside the CNT).

Preparation by pick and place allows for site-specific analysis and electron tomography which gives 3D information on the CNT distribution in contacts was outlined.

WP3 - Grafting of SWCNTs on Si

In this WP the capabilities of electro-grafting as an innovative technology for the deposition of ex-situ grown CNTs is evaluated.

At the start of the project, the state of the art was reported in two papers describing the attachment of CNTs (not the simple deposition) to surfaces. But the nanotubes were entangled in bundles and several layers of bundles were imaged by AFM. We have explored a variety of methods for the surface or end modification of nanotubes; both physical (ball-milling and plasma) and chemical (by reaction with amines and diazonium salts).

Physical modifications of CNTs: The sidewall passivation strategy using ball milling under a NH3 atmosphere was unsuccessful as the coating (by a polymer or a surfactant) was not stable and was removed during the process.
Plasma treatment of aligned MWCNTs was investigated. The high density of CNTs prevented functionalization of the nanotube sidewall. Thus, the functionalization was selective to the tips as only tips are in principle accessible. For this purpose, two techniques were tested. Ion beam using N2 was found to be efficient without destroying the alignment of the MWCNTs when the ions energy was decreased to the minimum value and by using very short treatment times (a few seconds). Up to 0.8% N was obtained. A more appropriate technique was also used to allow a higher level of functionalization and a higher selectivity towards the formation of NH_2 functions without destroying the alignment of the MWCNTs. The sample was placed in the post-discharge of Ar + N_2 microwave plasma. Up to 10.5% N was reached.
Chemical modifications of CNTs:

<u>On tips:</u> A chemical approach was also studied to functionalize the defect sites of the CNTs with amine functions since they are mainly located at the tips. Visualization of the functional groups was achieved by inducing formation of selenium particles very close to the functions. SEM characterization confirmed that most of the selenium particles, and thus most of the amine containing functional groups were introduced at the nanotube tips. The DWCNTs were functionalized with two types of amine functions: an alkyl and an aromatic amine; XPS indicated that the nitrogen incorporation was 3.6% and 3.2%, respectively.

On walls: We have concentrated our efforts on the surface modification by bifunctional molecules and specifically by ethylenedianiline and have selected diazonium chemistry as the most efficient process. We have explored both the modification of nanotubes and of surfaces and carefully characterized these modified species. In parallel we have investigated various possibilities for the dispersion of nanotubes that would be compatible with the grafting process. It was then possible to attach well dispersed nanotubes (that is with chemical bonds) the CNTs on blanket surfaces.
This sample reaction was repeated on Si bottomed trenches etched in SiO_2. It is remarkable that by simple tuning of chemistry, it was possible to attach selectively the CNTs at the bottom of the vias without any nanotubes on the SiO_2 walls or top. This is comparable to the state of the art reported at the same time in the literature [Error! Bookmark not defined., Error! Bookmark not defined.], but, in addition, we have been able to control the concentration of CNTs in the trenches.
The separation of metallic from semiconducting nanotubes has been attempted by using literature methods, but the separation is not yet sufficient for practical applications. The appropriate simple method needed to separate/enrich SWCNTs in one electronic type has not yet been found. To achieve this goal, much R&D is still necessary through multi-step processes. The best way is certainly the direct chirality control during the SWCNTs growth.

WP4 Electrical evaluation of CNTs in Si device structures (WPL B. Capraro, Intel)
WP4 aims to demonstrate electrically the compatibility of CNTs with Si technology. Test structures were designed and manufactured to enable growth and placement of the CNTs in WP2 in order to achieve suitable structures for electrical testing and characterization including a methodology to perform statistical analysis on the quality of the grown CNTs and their contacts. From these results a material-based roadmap has been produced in conjunction with the International Technology Roadmap for Semiconductors (ITRS).

In task 4.1, the project specifications were well researched in collaboration with IMEC and Liten, and delivered on time to the project co-ordinator. In addition to the requirements, a literature search study on metal contacting of CNTs was also delivered within the D1 report. The design and fabrication of Horizontal Growth Test Structures (HGTS) demonstrated the great collaboration and results orientation attributes exhibited by this work package and project Consortium. All partners (except Nanocyl) had significant input to the highly successful design brainstorm meetings, and consequent finalisation of the design requirements document generated by Intel Ireland. This resulted in the early delivery of M12 and D5, enabling both IMEC and Liten to start horizontal growth experiments earlier than expected. Despite being a manufacturing facility, fully loaded with Customer commitments, Intel Ireland were able to deliver a significant number of HGTS wafers, and some additional wafers to enable extra experimentation around catalyst deposition, analysis and CNT synthesis. The project Consortium was also able to agree legal terms to enable the use of these HGTS within other projects outside of CARBonCHIP.
For tasks 4.2 and 4.3, the project Consortium concentrated efforts on back end of line (BEOL) applications for CNTs, i.e. vias and interconnects. Because of the difficulties associated with chirality and band gap control required for front end of line (FEOL), it was soon realised that progress in BEOL would be faster. However, the work carried out in preparing the various electrical probing toolsets across the Consortia was

relevant to both FEOL and BEOL applications, and will be used in continued research. The toolsets that were eventually proven for the CARBonCHIP project were different and far more extensive than originally called out in the project DoW. This was explained at the project mid term review in Leuven (October 23rd 2007). WP4 has electrically analysed materials from all the other workpackages in the project, including zeolite occluded material (WP2), and pristine, functionalised and grafted CNTs (WP3). However, due to the lack of a significant large sample of synthesised CNT material, a fully comprehensive statistical analysis of CNT electrical properties is not yet complete. Statistics from WP2 horizontal growth (Liten) on tip HGTS was useful to improve the horizontal growth conditions, and determine which geometries and gap dimensions were significant in CNT growth quality and quantity. In addition, the lack of volume of samples has impacted the work required to determine a suitable electrical contact metal and process for CNT integration. Initial probe tip experimentation (in IMEC) and blanket deposition tests (in Intel) confirmed the literature search findings that Palladium (Pd) could be a suitable metal. All of the work performed in these tasks is duely reported in detail in D11 and D16. To compliment the top contact preliminary investigations, and to help with CMOS integration, initial experiments were successfully performed on BEST02 wafers with integrated CNTs using Chemical Mechanical Polish (CMP). This is envisaged to provide a flat metal deposition surface, with all CNT shells exposed to the metal deposition. This work is detailed in the month 24 Periodic Activity report.

In task 4.4, Intel Ireland were able to engage the CARBonCHIP project adequately within the International Technology Roadmap for Semiconductors Organisation (ITRS), with a representative (Jean Dijon, Liten) being a member of the newly formed "Emerging Research Materials Working Group" (ERM WG). Throughout the project duration, the ERM WG has seen participation from the CARBonCHIP project through considerable input in to the first ERM Chapter, published in February 2008, to the final results report out at the 2009 ITRS Spring Meeting held in La Hulpe (near Brussels) on 19th March 2009. Interest from this final results report out has been sparked across the ITRS Organisation, with the Interconnects WG requesting the CARBonCHIP report out also.

Also in WP4, Intel organised and hosted a Workshop designed to showcase and benchmark research activities across the Nanowire community. This was achieved as part of the European Research and Innovation Conference (ERIC) hosted by Intel Ireland on September 10-12th 2008. The Workshop event was attended by over 100 Researchers from across Europe and the United States, and comprised of eight presentations by prominent Researchers in their field from a total of five European Countries, as well as a panel session focusing on the question of "How to realise High Volume Manufacturing (HVM) in the Silicon IC Industry using these novel 1-D materials". This workshop satisfied M17 of the project during month 30 (originally planned for month 24, but pushed out to allow inclusion at the ERIC).

Additional activities of Intel Ireland (as WP4 leader) in the CARBonCHIP project are also recorded in detail, and include the organisation and hosting of a RAMAN Characterisation Workshop (WP2), and the establishment of a Nanomaterials Sample Shipping Guideline which was employed for the movement of research samples across the consortium.

In conclusion, the Intel Ireland silicon nanotechnology research team have very much enjoyed the research activities encountered within our first Framework Programme Project (CARBonCHIP), and look forward to continued collaborations with the

Consortium partners, and new partners in the future, to further the encouraging initial results.

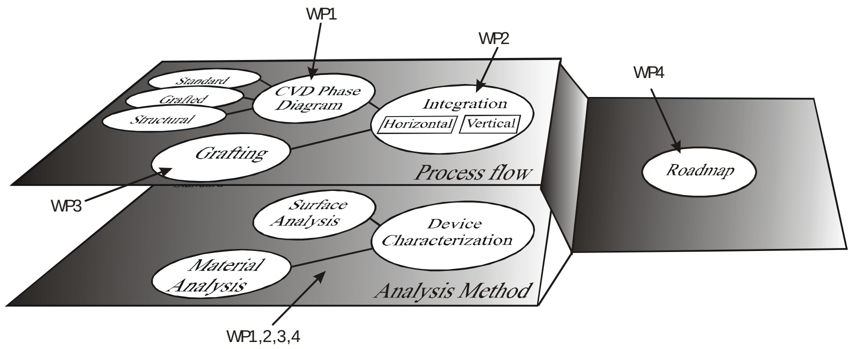

Fig. 5 Pert diagram showing the interdependencies between the four WPs in CARBonCHIP.

6. Project dissemination and use

a) <u>Dissemination</u>

This section summarizes the activities undertaken in relation to the use or dissemination of CARBonCHIP project results, including publications made, press releases, brochures etc. or any other dissemination activities carried out, such as presentations at conferences etc.

In total 57 actions have been undertaken to disseminate the results of the project through publications in peer reviewed journals, at scientific conferences or by patents. The results of the project have been published at various forums, leading journals and conferences. Also in total 4 patents were submitted for technologies developed in the project. Figure 1 shows the distribution of these actions over the main contributing partner (1st author, main inventor, etc.).

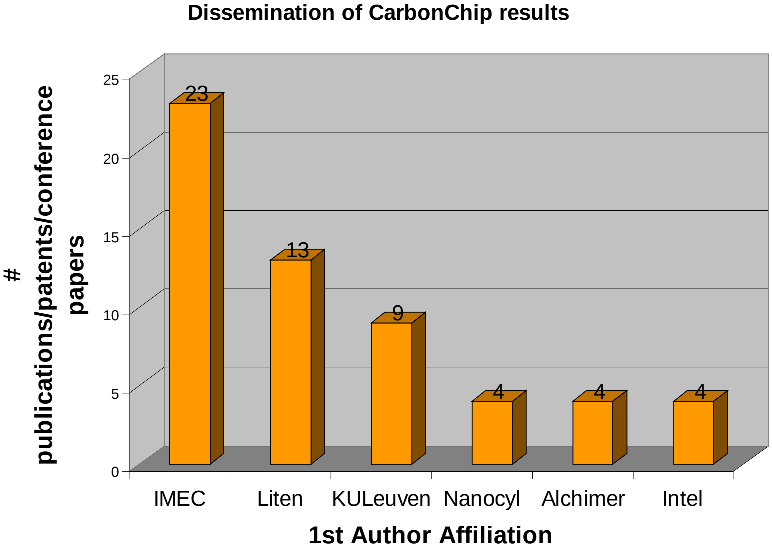

Figure 1 – Distribution of the number of disseminating actions finalized during the project over the 1st author partner affiliations

In order to disseminate the results of the project the consortium has also organized, besides publications and contributions at conferences, two workshops in the course of the project: one workshop intended to bring together, discuss and disseminate the project results related to the use of Ramam spectroscopy for the characterization of CNT's, whereas the second workshop intended to present the results of the project to other researchers active in the field of one-dimensional nanostructures. Besides these two own workshops the consortium has also presented the results of the project to the ITRS Spring meeting in La Hulpe, Brussels in March 2009 at the end of the project.

b) **Use and exploitation**

The in-situ growth of CNTs in WP1 together with ex-situ growth and subsequent grafting in WP3 on unpatterned substrates, converged in WP2 in a process flow for the integration of horizontal and vertical CNTs on patterned Si. At all stages of WP1, WP2, and WP3, analysis methods have been essential to develop a successful approach to device characterization, in particular electrical, the focus of WP4.

Overall, the results of CARBonCHIP form the baseline for technological assessment of CNTs and provide realistic routes for CNT technology development. The impact of the results are most clearly defined by the construction of a roadmap for the integration of CNTs on Si.

At the end of the project each partner has made up a plan for further use and exploitation of the project results. These are summarized below.

IMEC

IMEC will further develop the low-temperature deposition process of CNT's, which includes the study of the quality of CNT's grown at reduced temperatures. IMEC will also continue the implementation of CNT's in via's and the benchmarking with Cu via's. This also required to improve the density (in number of shells) of the CNT's. IMEC will continue to work on integration of zeolite occluded CNT's for horizontal interconnects in close collaboration with the KULeuven. Also IMEC intends to extend use of CNT's to other application areas: resonators, through-silicon via's (TSV) for 3D-integration and sensors. Finally IMEC will re-use the material analysis technology (MFM, Raman, P&P, Nanoprober etc.) developed in CarbonChip for future technology programs

In the future IMEC will submit new patents and publications. Also IMEC has reported already part of the results within it's core partner program. This is the industrial affiliation program funded by the world's major microelectronics industry: NXP, Infineon, Intel, Samsung, TSMC, Panasonic, Micron, Elpida, Hynix, PSC. The activities on CNT integration continue within this program, as part of the Interconnect and 3D program. Finally IMEC has started and plans to startup new projects which are based on the background knowledge builtup within CarbonCHip.

CEA-Liten

Liten will further work on the high density CNT material both for integration in vias structures through the FP7 Viacarbon project but also to use these materials for the core activity of Liten around energy (Fuel cells, solar cells and battery). The integration technology developed in the carbonchip project is already used in other European project like NanoRF and Viacarbon.

Liten will submit a new patent with alchimer on the integration of Nano Particles in devices Liten will publish scientific papers around the main results achieved in the project particularly around the phase diagram built in WP1 Liten will participate on the proposal of new projects on the integration of CNT's for nanoelectronic to go further in the direction of an industrial interconnect technology with CNT

Finally Liten will work on the enrichment of the CNT materials in metallic tubes through the French ANR project SOS nanotubes with the ultimate goal to produce CVD materials with a high metallic content for interconnects applications

Alchimer

Actions for the nanotube electrografting:

- Alchimer will not continue the development of the electrografting of nanotubes in trenches due to a modification of the commercial strategy.
- But scientific conferences and workshops are planned to expose the results and the methodology (e.g. RadiSurf, 9-10 Sept. 2009, Aarhus, Denmark).

Actions for the catalyst electrografting:

- Alchimer will continue to work on integration of catalyst nanoparticles in microelectronic structures in close collaboration with Liten.
- A new patent and publications are in preparation and will be submitted before the end of 2009.

Nanocyl

Nanocyl will further use the CVD set up for in situ growth synthesis that has been acquired (shared with IMEC) and so will continue the work on synthesis of vertically aligned carbon nanotubes in the frame of SOLHYDROMICS (EU project) in which the growth requirements are less drastic than in CarbOnChip. This work will be done in order to check the feasibility for membrane or electrode preparation for the Fuel Cell field. Moreover, the work performed in collaboration with Alchimer on the preparation of an aqueous dispersion of double wall carbon nanotubes may give rise to a Laboratory Grade product depending on the customer demand. And finally, CarbOnChip is the starting point for Nanocyl research on single wall carbon nanotubes sorting (metallic/semiconducting) as this topic is more and more common among the customer request.

K.U. Leuven

KULeuven will continue the study and development of the zeolite-CNT materials. The fundamental study of the interactions between zeolite framework and occluded nanocarbon will be continued, more especially on the effect of the zeolite on diameter and chirality control and the growth mechanism of the occluded CNTs. A further study of the implementation of the synthesis strategies for zeolite growth on chip is

planned, both for vertical and horizontal applications. The characterization platform built up during the CARBonCHIP project will be used for an in-depth study of the zeolite occluded nanotubes, also on-chip. Bilateral collaborations both with IMEC and Intel will be maintained.
Considering exploitation of the results, KULeuven will submit further publications on the results obtained during CARBonCHIP, and is also planning to submit new publications. New projects based on the background knowledge of CARBonCHIP have started and are planned for startup (PhD student Evelyne Bartholomeeusen and FWO project respectively). KULeuven is also planning to participate in a new proposal for FP7 in this field.

Intel

Intel Ireland as part of the Intel Corporation is subject to a technology roadmap which is designed to maintain the pace of Moore’s Law. Through a consistent two year technology cadence, Intel is able to deliver state-of-the-art technology and novel design architectures leading to new product introductions every year. This can only be achieved by engaging in new materials and process technology research across the globe, in order to capture potential options for high volume manufacturing (HVM). The Intel Research and Development pipeline requires many options to be explored in order to arrive at a suitable candidate for internal development and up-scaling for HVM. (The Intel Ireland site in Leixlip, Ireland, is one of Intel’s largest technologically advanced HVM sites, and the largest outside the United States). The European collaboration, CARBonCHIP represents one such relevant investigation into an alternative material and process technology which may be successful in entering the next phase of research. Key results from this project and many others like it are regularly reported in to the Technology Division responsible for new process technology research and development, as well as enabling the rest of the industry to avail of the latest results through engagement with the International Technology Roadmap for Semiconductors (ITRS) working groups. Intel currently Chair the ITRS, and lead the Emerging Research Materials (ERM) working group.
Intel Ireland is very keen to continue the investigation of carbon nanotube (CNT) technology and integration within the European Union, and is such working with the key partners of CARBonCHIP to develop a new proposal for FP7 (ICT Call 5). This proposal will continue to investigate the novel proof of concept involving zeolite crystallite templates, as well as continuing to investigate the critical electrical aspects of the CNT integration (contact resistance etc.). The improvement in growth density to realise suitable back-end-of-line interconnects is the subject of an already active FP7 FET Open project “Viacarbon”.
In addition to the European FP activities, Intel Ireland is the founding Industrial partner of the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) located at Trinity College Dublin and University College Cork. One aspect of the nanotechnology research being carried out, utilising Intel Ireland Researchers in Residence, relates to the use of CNTs as interconnects. The published results from both CARBonCHIP and Viacarbon form part of the state-of-the-art findings for projects being carried out within this institution.