PUBLISHABLE SUMMARY

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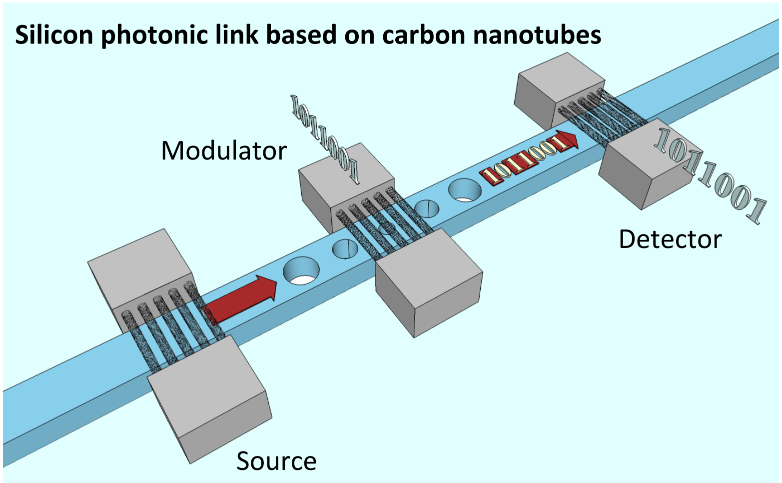
OVERVIEW

In the last few years, silicon has become a material of choice for an increasing number of applications in photonics that support competitiveness of industrial strongholds. These targeted applications are mainly based on the use of optoelectronic devices (i.e. light sources/modulators/detectors) operating in telecom wavelength range for the development of optical circuits. Today, there are numerous photonic devices to emit, propagate, modulate and detect light at the chip-scale. However, the integration of all the photonic building blocks on the same circuit is considered to be very challenging, because several materials are used including Si for modulator, Ge for detector and III-V semiconductors for laser sources. The integration of all these materials on silicon is technically possible, but as different and sometimes non-compatible processes are used, the resulting scheme is not cost-effective, and consequently reduces the use of silicon photonics for a broad application domain.

Primary goal of the CARTOON project was the development of a novel strategy for hybridizing silicon based photonic devices, exploiting carbon nanotube (CNT) as integrated light source, modulator and detector in the near infrared wavelength range. In particular we chose semiconducting single wall carbon nanotube (s-SWNT) since they are a very versatile material, presenting at the same time very good electronic and optical properties. They display strong room temperature photoluminescence, in the NIR wavelength range, as well as strong thermal photostability. Emission can be tuned by selecting a precise nanotube diameter and chirality. They can integrate to made diodes and field effect transistors opening the possibility of using electrical pumping for luminescence and photo detectors. Additionally their electronic transitions, via predicted Stark and Kerr effects, could also be used to obtain modulation effects. Therefore, carbon nanotubes are very good candidates to solve integration issues in silicon photonics, and to make cost-effective and reliable photonics. Furthermore, a side advantage of the use of nanotubes for photonics is that the current research on the use of nanotubes for nanoelectronics will facilitate the integration between photonics and electronics.

Then, the project addresses the hybrid integration route of carbon nanotubes on silicon photonics platform to perform key advances in waveguide detectors, integrated optical modulators and optical source. As a schematic view, the following figure presents a vision of the project final goal highlighting the integration of carbon nanotubes in a silicon photonics circuit.



The CARTOON project gathers four leading academic experts on Nanophotonic characterizations (UNIFI), electrical and optical properties in carbon nanotubes (CEA), the molecular modeling (TUD) and silicon photonics (UPSUD)

The project reposed on six major cornerstones achieved in the three years:

(i) Photodetection in the 1.3-1.6µm wavelength range,
(ii) Demonstration of third order non-linearity in s-SWNTs for optical modulators effects
(iii) s-SWNT emission integrated in Si photonic nanoresonators and guided with low losses in long Si waveguide
(iv) Electrically pumped s-SWNT emission.
(v) Integrated photodetector based on SWNT in silicon
(vi) Integrated Si laser based on SWNT

Each of these cornerstones is a world's premiere and constituted a scientific breakthrough. In addition to these goals expected in the proposals, additional major achievements have been obtained in:

(a) understanding the role of polymer interaction in the s-SWNT selection,
(b) implementing efficient protocols for selecting semiconductor nanotubes, with increased density,
(c) novel s-SWNT growth based on cloning,
(d) novel near field imaging of photonic modes based in Fano lineshape and resonant scattering.
(e) efficient integration scheme in silicon photonics platform for nano-objects.

In a long term vision the establishment of this new state of the art and advanced know-how on nanotechnology, nanooptics and optoelectronic devices based on s-SWNT will allow developing and addressing a broad range of applications in information technologies

WORK PERFORMED IN THE PROJECT, MAIN RESULTS

This project covers many aspects of the materials, molecular simulations, fabrication processes, design of photonic/optoelectronic structures and characterization at different scales (from unique carbon nanotube to devices). As a whole, the consortium comprises a value chain covering from material science to devices, which as an outcome will establish a new state of the art for the development of carbon nanotubes based photonics in silicon and will develop an advanced know-how on hybrid integration in silicon photonics platform. This project will also provide strategic knowledge and information favoring the EU technological progress and competitiveness in the key technological area of silicon photonics. Some details can be found on the CARTOON web site:

http://cartoon.ief.u-psud.fr/CARTOON/Welcome.html

During year 2 and year 3 of the CARTOON, the consortium has carried out important efforts in order to meet the final objectives of the project. Particularly, the last period (year 2 and year 3) has allowed producing 5 important deliverables corresponding to technical reports on (1) the extraction of semiconducting carbon nanotubes (WP1), (2) the modeling and experimentation of optical characteristics of SWNT network (WP2), (3) the transport characteristics, carrier injections, environment effects and EL generation (WP3), (4) the carbon nanotubes' integration on silicon platform (WP4), and (5) the optoelectronic devices based on SWNT (WP5). Additionally, two reports have been provided one deliverable on the final plan for use and dissemination of foreground (WP6) and a summary project work from M12 to M24 covering all WP. A series of 7 Milestones was provided in year 2 and one in year 3 as decision points to reach objectives at the end of the project:

The progress achieved toward the objectives of the 2nd and 3rd years as well as the highlights for each work package can be summarized as follows:

WP1 (Semiconducting carbon nanotube extraction and characterization) **M12- M36**

- ✓ Demonstration of a strong increase of the concentration of SWNTs at 1.3 µm and 1.55 µm
- ✓ Determination of the extraction mechanisms of SWNT
- ✓ Alignment of semiconducting carbon nanotubes emitting at 1.55µm
- ✓ Demonstration of the efficiency of SWNT cloning
- ✓ Determination of the environment effect on optical properties

WP2 (Interaction of SWNTs with polymers: modelling and characterization) **M12- M36**

- ✓ - Modeling and theoretical investigation of the influence of polymers on the electronic structure and optical properties of SWNTs,
- ✓ - Experimental study of the influence of polymers on optical properties of SWNTs,
- ✓ - Simulation of atomic structures of SWNT-SWNT contacts, also with polymers,
- ✓ - Study of contact resistance, effect of polymers,
- ✓ - Calculations of charge transport along SWNT/polymer networks,
- ✓ - Comparison of experimental and theoretical results, feedback to WP3 and WP4.

WP3 (Carrier transport and contact studies) **M12- M36**

- ✓ Removal of excess polymer wrapping CNTs
- ✓ Demonstration of the aligned and dense nanotube structures.
- ✓ Successful studies of the carrier injection/ collection conditions to achieve photodetector and electroluminescent device
- ✓ Theoretical simulation of the interaction polymer/nanotube
- ✓ Theoretical study of semiconducting-SWNT/metallic-lead interface and about charge injection into the SWNT network.

WP4 (Integration) **M12- M36**

- ✓ Optimized design of waveguides, grating couplers and cavities

- ✓ Optimized silicon process for the demonstration of low loss photonic structures and high Q-factor cavities.
- ✓ Development of a flexible and extremely sensitive near-field technique to directly evidence the optical modes of CNTs-on-Si structures and the CNTs-light/matter interactions.
- ✓ Strong CNTs luminescence enhancement in various cavity-based configurations.
- ✓ Demonstration of the strong light coupling from SWNT emission to the Silicon waveguides
- ✓ Demonstration of the PL enhancement in resonators and cavities including ring resonator, microdisk, photonic crystals, nanobeam cavity.
- ✓ Optimization of the integration of SWNT into Silicon platform

WP5 (Integrated optoelectronic devices) **M12- M36**

- ✓ Gain measurements around λ=1550nm.
- ✓ Strong photoluminescence enhancement in several integration schemes by both vertical and waveguide-edge pumping
- ✓ Development of a set-up to investigate the $X^{(3)}$ properties of CNTs thin film layers deposited on silicon waveguides for optical modulation.
- ✓ Development of SiN platform
- ✓ Demonstration of the first negative Kerr effect in SWNT
- ✓ Demonstration of the impact of the carrier into silicon waveguides
- ✓ Demonstration of surface illuminated SWNT photodetection
- ✓ Demonstration of integrated SWNT photodetector in silicon waveguide
- ✓ Demonstration of optically pumped integrated laser on silicon

Numerous breakthroughs have been obtained and the project reached most of its goals. Indeed, after theoretical modelling of polymer sorting (elucidating the competition between CNT bundling and adsorption of polymer chain on CNT sidewalls) and an optimization of the selection protocols with two different polymers, we obtained two classes of high purity s-SWNTs: HiPCO for emission at 1300 nm and Laser Ablation (LA) for emission at 1550 nm. They display strong room temperature photoluminescence (PL), as well as strong thermal photostability, with no bleaching or blinking. A novel scheme of preparation has been also developped: the cloning of s-SWNT.
SWNTs were integrated on SOI devices with designed metallic contacts demonstrating SWNT-FET with large On/Off current ratio. Both LED and photodetectors in the IR telecom wavelength have been also demonstrated for the first time.

Large effort has been dedicated to design and fabricate Si photonic structures for optimizing the coupling between the excitons in s-SWNT and the photonic modes. A novel IR near field imaging method has been developed based on Fano resonances in resonant scattering with spatial resolution better than 100 nm in the IR. Integration on photonic resonators has been demonstrated enhancing the PL intensity and largely increasing its time and spatial coherence. Integration of Si resonators with linear waveguides (WG) was also pursued and the SWNT-PL was successfully and guided in Si WGs for macroscopic length with low losses. Modulation by non-linear effect in SWNT has been more difficult than expected since it is hidden by intrinsic nonlinearities of Si; still the SWNT third order non-linearity has been measured with the first experimental demonstration of negative Kerr index for PFO/SWCNTs layers. Finally lasing on Si photonics was the most sought after and debated result of the whole Si photonic community. We demonstrated lasing action from s-SWNT integrated in different Si photonic resonators.

As initially proposed and in order to achieve those objectives, the tasks have been divided between the partners:

- ✓ PSUD was involved in the coordination of the project, the nanofabrication of silicon photonic structures, the extraction of semiconducting CNT emitting at 1.3µm, the characterization of integrated photonic structures.
- ✓ TUD was involved in the simulation of CNT interaction with polymer to define the best configuration to efficiently extract semiconducting CNT
- ✓ UNIFI was involved in the PL characterization of extracted CNT, the definition of PL behavior of CNT, in SNOM measurements, in integrated PL characterisation
- ✓ CEA was involved in the extraction of semiconducting CNT emitting at 1.55µm, their optical characterizations, the study of CNT contacts, the fabrication and characterization of emitter and photodetectors.

Very strong interactions between all partners have been necessary to reach these important breakthroughs. There has been an excellent communication between the 4 partners in charge of the closely interacting work packages.
These interactions between partners have been done on a regular basis (visit at partners' site or exchange of numerous samples, and data via emails or the web platform):

- ✓ Interactions between PSUD, CEA, UNIFI and TUD on the CNT extraction
- ✓ Interactions between UNIFI, PSUD and CEA on PL measurements. 1 PhD student and 1 Engineer exchanges have been carried out (One from UNIFI and one from PSUD)
- ✓ Interactions between TUD, CEA, PSUD and UNIFI on polymer interactions with CNT
- ✓ Interactions between CEA, PSUD, UNIFI and TUD on CNT characterizations
- ✓ Interactions between PSUD, TUD, and CEA on CNT contacts
- ✓ Interactions between CEA, PSUD, UNIFI and TUD on photonic device characterizations

POTENTIAL IMPACT AND USE

According to the impressive results obtained during CARTOON project, the potential impact and use of the project is huge. Indeed, as previously reported numerous breakthroughs have been obtained and pave the way to development new horizon of carbon nanotube photonics.

The major scientific impacts that the project will be faced are the following:

- The development of a reliable technologies for the different experimental protocols of a SWNT extraction, dispersion in polymers, integration in photonic structures, doping and fabrication of electrical contacts.
- A better understanding of the mechanisms involved in SWNT/PFO interaction and in electrical contact on a SWNT network.

The demonstration of hybrid integration scheme on silicon platform for nano-objects including SWNT, wires, Chalcogenizes, grapheme…

- The development of optoelectronic devices based on SWNTs integrated in silicon platform.

These results contribute directly to strengthen European industries and RTD in the emerging domain of photonic components and systems. CARTOON project will provide us compact and low power consumption photonic integrated circuits and their integration with electronics.

At long term, the CARTOON project paves the way to provide:

- An alternative of optoelectronic hybrid device integration with a high throughput in terms of cost, flexibility, robustness… The obtained breakthroughs pave the way on new avenue towards optical communication and computing (interconnect intra-chips, inter-chips, access network).
- A new solution to co-integrate photonic and electronic together based on the use of SWNT, which is a very important goal in the route of ICT.

In conclusion, our approach developed in the CARTOON project might overcome the well-known bottleneck of poor optoelectronic properties of Silicon photonics in the telecommunication window by aiming to push the optical properties of the SWNT to unprecedented values in term of efficiency, stability and wavelength range. This is by itself a fundamental achievement in the field of nanotechnology. Furthermore, the CARTOON project paves the way on new applications including optomechanisms, biosensing, quantum optics…

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