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Carbon Nanotube Photonics: Light emission in silicon and optical gain

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1. Introduction

For several years, silicon photonics have been extensively studied to overcome the limitation of metallic interconnects in microelectronics circuits. Although silicon-on-insulator substrates allow compact photonic structure due to the high contrast between silicon and silica and low loss propagation, silicon is an indirect bandgap material with rather poor optoelectronic properties. This assessment leads to consider alternative materials for the active devices in silicon photonics technology, and among them, carbon nanotube are a proemining candidate thanks to their ability to emit, modulate and detect light in the wavelength range of silicon transparency.

We report on the use of carbon nanotube for photonic application. First, we show how a polyfluorene assisted extraction process allow to select only semiconducting nanotubes (s-SWNT) without any traces of remaining metallic nanotubes [1]. This leads to the first experimental demonstration of a strong optical gain of 160 cm-1 in (8,7) s-SWNT at room temperature [2].

We will then report on the first integration of absorption and emission properties of carbon nanotubes in silicon waveguides, leading to the demonstration of the temperature independent emission up to 100°C from carbon nanotubes in silicon at a wavelength of 1.3 µm [3].

2. Carbon nanotube photonics

Semiconducting carbon nanotube extraction

Previously considered as a forever “black” material, carbon nanotubes came under the spotlights the day of the discovery of carbon nanotubes' photoluminescence upon encaapsulation into micelles surfactant. Today, carbon nanotube became an emerging material for nanophotonics and optoelectronics. Indeed, it has recently been shown that s-SWNTs could be used as strong light emitters in the near-IR, thanks to their efficient excitonic recombination across a direct band gap. However, there are several mechanisms in raw carbon nanotubes that offer non radiative paths, seriously hampering their emission efficiency. This was up to now a major hindrance to potential applications.

We will show that s-SWNTs could be efficiently extracted using an ultracentrifugation process assisted by a polyfluorene polymer (PFO), leading to the formation of optical quality PFO embedded s-SWNTs thin films. The polyfluorene used in this study has a special affinity with a certain kind of s-SWNT, and allow extraction of a limited extend of s-SWNT chiralities, without any remaining traces of metallic nanotubes (m-SWNT) or catalyst particles in the extracted nanotubes [1].

Photoluminescence enhancement

The evolution of s-SWNT optical properties as a function of m-SWNT concentration was studied by photoluminescence, absorption and Raman spectroscopies. More than showing in evidence PFO selectivity for high chiral anges s-SWNTs, this study underlines the role of purification to lower optical losses in s-SWNT/PFO thin layers. In particular, a strong enhancement of s-SWNT emission when in absence of m-SWNT will be reported [4]. (Fig. 1)

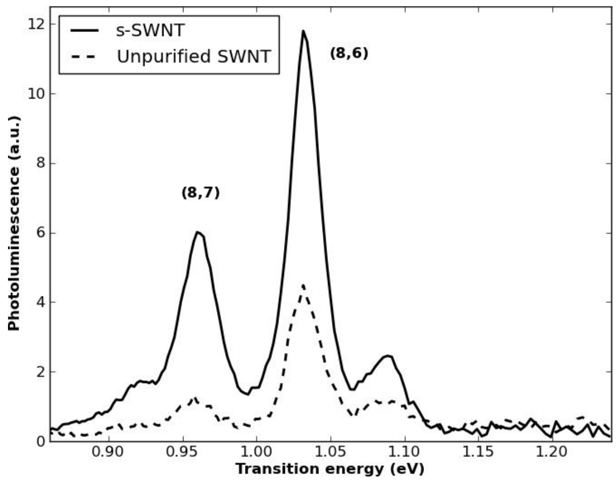

Fig. 1: Enhancement of (8,6) and (8,7) s-SWNT photoluminescence compared to unpurified SWNT material.

Optical gain in s-SWNT

This photoluminescence enhanced s-SWNT/PFO film was further investigated using optical gain determination techniques. Several methods, such as Variable Strip Length (VSL) method (Fig. 2), were performed, leading to the first experimental demonstration of a strong optical gain of 160 cm^{-1} in (8,7) s-SWNT at room temperature. Special emphasis will be put on the s-SWNT extraction, as optical gain could not be achieved in a raw or lowly extracted sample, presumably due to interactions with remaining m-SWNTs [2].

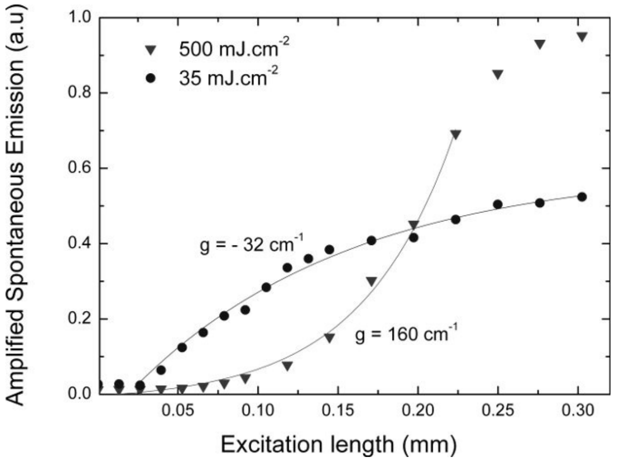

Fig. 2: Variable Strip Length method performed on s-SWNT/PFO sample. A gain behavior of 160 cm^{-1} is shown in evidence for high pumping fluency (500 mJ·cm^{-2}), while no gain regime is seen under low pumping fluency.

Integration with silicon photonics technology

The emergence of “Carbon Nanotube Photonics” for broad application domains (e.g. optical interconnects, telecommunications and biophotonics) will have to go by the integration of carbon nanotubes with existing photonics technology. The emerging and more and more considered photonic material is the silicon. It is obvious that the development of “Carbon Nanotube Photonics” has to be done within the framework of silicon platform, with optoelectronic devices based on carbon nanotubes (light source, modulation and detection) while the integrated light guiding structures will be performed by silicon waveguides.

In order to achieve this mutation of silicon photonics towards carbon, we will present the first integration of s-SWNT in silicon photonics structures. (Fig. 3)

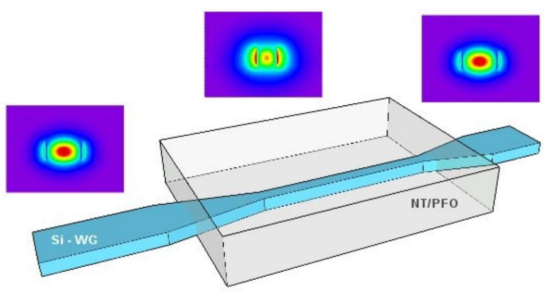

Fig. 3: Integration scheme of carbon nanotube based PFO layer with silicon waveguide. Input and output are single mode silicon waveguide with a height of 220 nm and a width of 450 nm ; the optical mode is strongly confined inside the waveguide. In the middle, the waveguide width is reduced down to 200 nm, and the optical mode is confined outside the silicon core.

We will emphasize how to achieve an efficient coupling between carbon nanotubes and silicon waveguides. We will also demonstrate the light generation in silicon from carbon nanotubes with a temperature-indepedent emission up to 100°C at a wavelength of 1.36 µm [3] (Fig. 4).

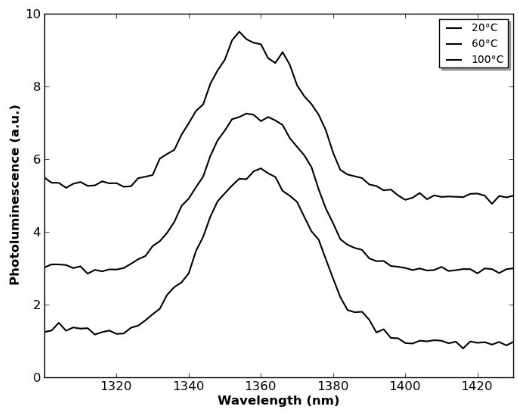

Fig. 4: Photoluminescence of (9,7) s-SWNT at 1.36 µm throught a silicon waveguide, to a temperature up to 100°C. Spectra were vertically shifted for clarity.

3. Conclusions

Modern single wall carbon nanotubes became an exciting materials for optic and photonics applications due to significant advances in nanotubes sorting and thin-films preparations.

We will present how PFO extracted s-SWNT displays a strong optical gain of 160 cm-1 at 1.3 µm, and the photoluminescence coupling of those nanotubes into silicon photonics waveguides. This is a significant milestone towards emergence of “Carbon Nanotube Photonics”.

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Appendix

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