Shaping the optical properties of carbon nanotubes via chirality- selective resonant enhancement in silicon micro-ring resonators

Elena Durán-Valdeiglesias, Weiwei Zhang, Carlos Alonso-Ramos, Samuel Serna, Xavier Le Roux, Delphine Marris-Morini, Marta Reig, Niccolò Casselli, Francesco Biccari, Massimo Gurioli, et al.

To cite this version:

Elena Durán-Valdeiglesias, Weiwei Zhang, Carlos Alonso-Ramos, Samuel Serna, Xavier Le Roux, et al.. Shaping the optical properties of carbon nanotubes via chirality- selective resonant enhancement in silicon micro-ring resonators. European Conference on Integrated Optics (ECIO 2019), Apr 2019, Ghent, Belgium. cea-02329266

HAL Id: cea-02329266

https://hal-cea.archives-ouvertes.fr/cea-02329266

Submitted on 23 Oct 2019

Shaping the optical properties of carbon nanotubes via chirality-selective resonant enhancement in silicon micro-ring resonators

Elena Durán-Valdeiglesias[1,*], Weiwei Zhang[1,†], Carlos Alonso-Ramos[1], Samuel Serna[1], Xavier Le Roux[1], Delphine Marris-Morini[1], Marta Reig[2], Niccolò Casselli[3], Francesco Biccari[3], Massimo Gurioli[3], Arianna Filoramo[2], Eric Cassan[1], and Laurent Vivien[1]
[1] Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Sud, Université Paris-Saclay, C2N, Orsay 91405, France
[2] CEA Saclay, IRAMIS, NIMBE (UMR 3685), LICSEN, Bât. 125, F-91191 Gif-sur-Yvette, France
[3] Department of Physics, University of Florence. European Laboratory for Non-linear Spectroscopy, 50019 Sesto Fiorentino (FI), Italy
e-mail: Elena.Duran@u-psud.fr
† Current address: Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

ABSTRACT

Semiconducting single walled carbon nanotubes (s-SWNT) have an immense potential for the development of light sources in the silicon photonics platform. However, two major challenges still need to be addressed: the limited interaction between s-SWNTs and Si waveguides and the single-chirality selection. Silicon micro-ring resonators may overcome the first limitation by exploiting resonant light recirculation. Here, we demonstrate that Si ring resonators can also provide SWNT chirality-selective photoluminescence resonance enhancement, releasing a new degree of freedom to shape the optical properties of s-SWNT. Specifically, we experimentally show selective emission enhancement of either (8,6) or (8,7) SWNT chiralities present in a high-purity polymer-sorted s-SWNT solution by judicious micro-ring geometry design. In addition, we harness the large index contrast of the Si platform to experimentally demonstrate that, opposite to the common knowledge, transverse-magnetic (TM) optical modes can efficiently interact with drop-casted s-SWNTs arranged along the chip surface.

Keywords: carbon nanotubes, hybrid silicon photonics, photoluminescence.

1. INTRODUCTION

Semiconducting single walled carbon nanotubes (s-SWNTs) are direct band gap semiconductors exhibiting absorption, photo- and electro-luminescence at room temperatures from the visible to the mid-infrared wavelengths [1]-[3]. These properties make s-SWNT an appealing material for the realization of light sources and detectors for the silicon photonics technology. Driven by this application, several implementations of hybrid integration of s-SWNT with silicon have been reported, based on micro-ring resonators [4,5] and photonic crystal micro-cavities [6,7]. All these examples focus on the optimization of the interaction between s-SWNT and the transverse-electric (TE) waveguide modes. It is well known that transverse-magnetic (TM) modes in Si wires can provide strong evanescent field that can be leveraged to enhance light interaction with the waveguide surroundings. However, due to the dipole-like behaviour of the s-SWNT, interacting with the main TM electric field component (vertical orientation) would require vertically aligning the s-SWNT on the waveguide surface [8]. Although technically possible, this approach may have a limited scalability. Here we show that TM waveguide modes can have strong interaction with s-SWNT aligned parallel to the chip surface, deposited by simple and scalable drop-casting technique. On the other hand, polymer-based s-SWNT processing techniques, allow removing the vast majority of impurities in s-SWNT solutions, but have problems in achieving single SWNT chirality selection. Here we experimentally demonstrate that proper micro-resonator design enables chirality-selective resonant enhancement of the photoluminescence signal. This novel approach opens a new degree of freedom to implement single-chirality selection in hybrid Si-SWNT devices.

2. RESULTS

The first step is to study the interaction of the TE and TM waveguide polarizations with s-SWNT deposited on top. To do this we consider separately the electric field component aligned along the propagation direction, E_z, and the transversal components aligned transversally, along the chip surface, E_x, and perpendicularly, E_y. These three field orientations would maximize interaction with s-SWNTs aligned with the z, x and y axis, respectively (see Fig. 1). We calculate the dielectric field confinement ξ_{cladd} [9] on top of the waveguide, where the s-SWNT are, for the three electric field components as a function of the waveguide width, W_{wg}, considering waveguide modes with TE and TM polarizations. As shown in Fig. 1 the highest ξ_{cladd} is achieved for the E_y component from the TM mode. However, such configuration requires s-SWNT aligned vertically on the chip surface, rendering this solution technologically challenging. On the other hand, we find that the E_z component in the TM mode can provide a larger dielectric field confinement than the E_x component in the TE mode, which is conventionally optimized for hybrid SWNT integration. Then, we then chose a waveguide width of W_{wg}=350 nm, yielding $\xi_{cladd} \geq 4.5\%$.

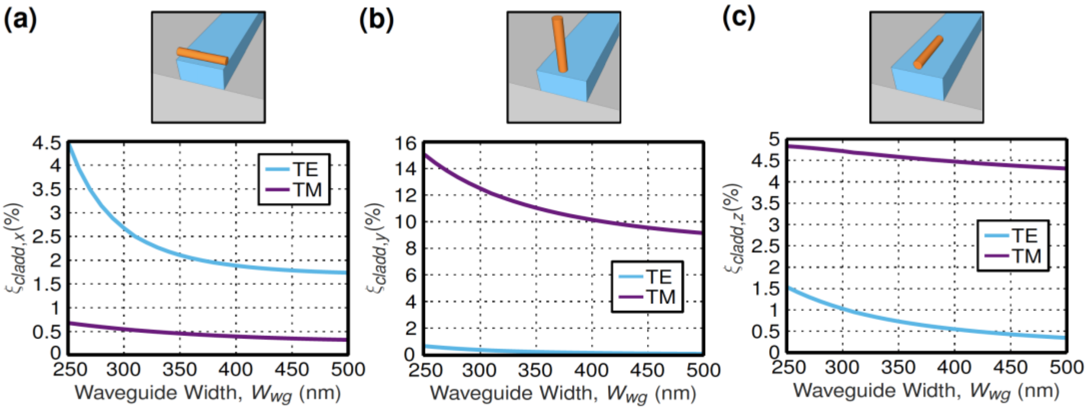

Figure 1. Dielectric field confinement on top of the waveguide, where s-SWNT are, as a function of waveguide width for (a) transversal Ex, (b) transversal Ey and (c) longitudinal Ez components of both fundamental TE and TM modes at wavelength of 1300 nm. Top panels schematically show preferred SWNTs orientation for maximized light-SWNTs interaction for each component of the electric field.

For the implementation of the micro-resonator, we implement an all-pass scheme with an asymmetric configuration where the ring and bus waveguides have a different width (see inset in Fig. 2). The goal is to yield a strong light recirculation enhancement only in a narrow wavelength range, matching the emission of a given s-SWNT chirality. This scheme allows promoting resonance enhancement of only one s-SWNT chirality, even if the solution contains different chiralities. As the bus and ring waveguides have different widths, modes propagating through them have different phase propagation constants, precluding perfect phase matching, thus resulting in a strong chromatic dispersion of the bus-to-ring coupling ratio, i.e., for a given bus-to-ring gap (G), critical coupling condition is achieved for a comparatively narrow bandwidth. Following this asymmetric coupling approach, the ring has a waveguide width of W_{wg}=350 nm (optimized for light-s-SWNT interaction) and the bus waveguide has a width of W_{bus}=270 nm. We chose a ring radius of 5 µm yielding a free-spectral range near 10 nm, easily discernible with our spectrometer.

We fabricated the silicon ring resonators by electron-beam lithography and dry etching. Then the devices were covered with a hydrogen silses-quioxane (HSQ) cladding, opening interaction windows on top of the bus-to-ring coupling region. Finally, we deposited a high-purity s-SWNT solution by drop-casting. This solution contains s-SWNTs with two chiralities, (8,6) and (8,7), with emission near 1200 nm and 1300 nm wavelength, respectively [10]. The bus-to-ring gap was varied between 80 nm and 270 nm.

To characterize the photoluminescence enhancement, we excited the s-SWNTs from the surface of the chip using a continuous wave Titane Sapphire (Ti:Sa) laser with 1.5 mW power at 735 nm wavelength (S22 excitonic transition of s-SWNT). The generated photoluminescence, coupled to the waveguide, was collected at the chip facet with a polarization maintaining lensed fiber. A polarization rotator is used at the input to set the excitation polarization and a polarization filter is used at the output to select TE or TM polarization for the photoluminescence signal. The collected spectrum was analyzed with a 320mm long spectrometer with a 950 lines/mm grating, coupled to a nitrogen-cooled InGaAs array.

In Fig. 2a we present the upper envelope of the collected photoluminescence signal in the TM polarization as a function of the wavelength for different bus-to-ring gaps. As expected from the micro-ring design, photoluminescence enhancement occurs in a narrow wavelength range, with a central wavelength increasing with the gap. This way, smaller gaps yield stronger photoluminescence signal for (8,6) s-SWNTs, while larger gaps promote emission from (8,7) chirality.

To compare the photoluminescence resonant enhancement for (8,6) and (8,7) chiralities, we define the resonance enhancement factor, as the ratio between photoluminescence intensity on resonance (I_{ON}) and off resonance (I_{OFF}), $\alpha = I_{ON}/I_{OFF}$. Then we defined the figure of merit β, as the ratio between the resonance enhancement factor for the (8,6) chirality (at 1200 nm wavelength) and the (8,7) chirality (at 1300 nm wavelength).

Figure 2b presents the figure of merit β, estimated from the measurements in Fig. 2a. It is apparent that smaller gaps favour resonance enhancement of s-SWNTs with (8,6) chirality ($\beta < 0$), while larger gaps promote the resonant enhancement of s-SWNTs with (8,7) chirality ($\beta > 0$). In addition, it can be observed that the maximum enhancement region shifts towards longer wavelengths, as the gap increases, in good agreement with the ring resonator design. These results show that by engineering the dimensions of the micro-ring resonator, it is possible to promote resonance enhancement of the emission of a single s-SWNT chirality present in a complex mixture comprising different chiralities.

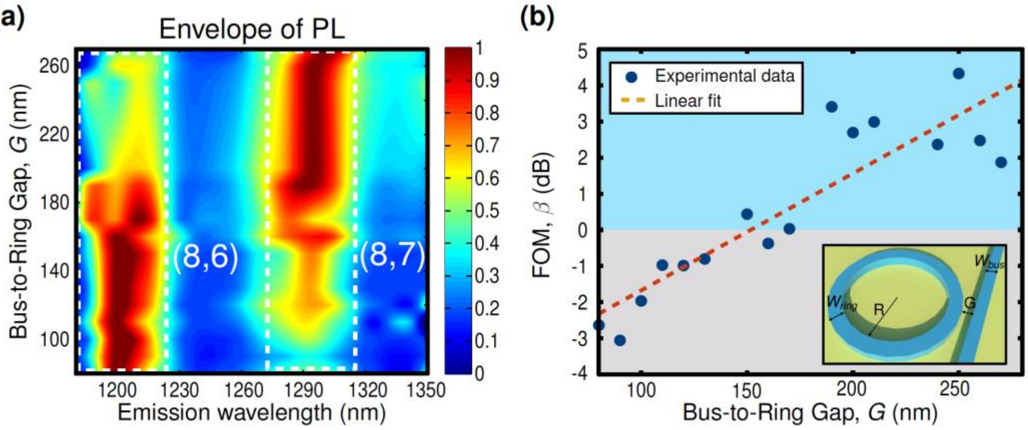

Figure 3. (a) Measured normalized photoluminescence spectrum of SWNTs deposited by drop-casting on Si micro-ring resonators with radius of R= 5 µm, and different bus-to-ring gap (d) Figure of merit estimated from measurements.

3. CONCLUSIONS

Semiconducting single walled carbon nanotubes have been recently identified as a promising solution for the implementation of light sources in silicon photonics. Despite the high purity achieved by polymer-based s-SWNT processing techniques, single SWNT chirality selection remains a challenge. In this work, we demonstrate that by integrating the s-SWNT onto Si micro-ring resonators, it is possible to realize SWNT chirality-selective resonant enhancement of the emission, opening a new SWNT chirality selection mechanism. We experimentally show selective promotion of the resonant enhancement of either (8,6) or (8,7) s-SWNT chiralities present in our solution. Unlike previously reported hybrid Si-SWNT devices [4]-[7], the ring resonators shown here harness the strong longitudinal electric field component of the TM mode to interact with the SWNT. These results open two new degrees of freedom, waveguide mode polarization and selective chirality resonance enhancement, for the implementation of s-SWNT-based devices for the silicon photonics platform.

ACKNOWLEDGEMENTS

The sample fabrication has been performed at the Plateforme de Micro-Nano-Technologie/C2N, which is partially funded by the “Conseil Général de l’Éssonne”. This work was partly supported by the French RENATECH network.

REFERENCES

[1] S. Wang, *et al.*: High-performance carbon nanotube light-emitting diodes with asymmetric contacts, *Nano Lett.*, vol. 11, pp. 23–29, Nov. 2010.
[2] F. R. Wang, *et al.*: High conversion efficiency carbon nanotube-based barrier-free bipolar-diode photodetector, *ACS Nano*, vol. 10, pp. 9595–9601, Sep. 2016.
[3] M. Balestrieri, *et al.*: Polarization-sensitive single-wall carbon nanotubes all-in-one photodetecting and emitting device working at 1.55 µm, *Adv. Funct. Mater.*, vol. 27, pp. 1702341-1-1702341-9, Oct. 2017.
[4] A. Noury, et al.: Enhanced light emission from carbon nanotubes integrated in silicon micro-resonator, *Nanotechnol.*, vol. 26, pp. 345201-1-345201-8, Aug. 2015.
[5] E. Durán-Valdeiglesias, *et al.*: Integration of carbon nanotubes in silicon strip and slot waveguide micro-ring resonators, *IEEE Trans. Nanotechnol.*, vol. 15, pp. 583-589, July 2016.
[6] T. H. C. Hoang, *et al.*: Narrow-linewidth carbon nanotube emission in silicon hollow-core photonic crystal cavity, *Opt. Lett.*, vol. 42, pp. 2228–2231, June 2017.
[7] R. Miura, *et al.*: Ultralow mode-volume photonic crystal nanobeam cavities for high efficiency coupling to individual carbon nanotube emitters, *Nat. Comm.*, vol. 5, pp. 5580-2-5580-5, Nov. 2014.
[8] E. Durán-Valdiglesias, *et al.*: Tailoring carbon nanotubes optical properties through chirality-wise silicon ring resonators, *Sci. Rep.*, vol. 8, pp. 11252-1-11252-8, July 2018.
[9] R. M. Osgood, *et al.*: Engineering nonlinearities in nanoscale optical systems: physics and applications in dispersion-engineered silicon nanophotonic wires, *Adv. Opt. Photonics.*, vol. 1, pp. 162-235, Jan. 2009.
[10] N. Izard, *et al.*: Semiconductor-enriched single wall carbon nanotube networks applied to field effect transistors, *Appl. Phys. Lett.*, vol. 92, pp. 243112-1-243112-3, June 2008.